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WASHINGTON UNIVERSITY IN ST. LOUIS

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Fields Under the Hoof: characterizing plant cultivation of agropastoralists in Bronze and Iron
Age Inner Asia (3000 BCE - 1000 CE)

by

Melissa M. Ritchey

A dissertation presented to
Washington University in St. Louis
in partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

May 2025
St. Louis, Missouri

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Washington University in St. Louis

May 2025

Dedicated to the ancient communities whose lives and practices I have the privilege to breathe
life into once more.

ABSTRACT OF THE DISSERTATION

Fields Under the Hoof: characterizing plant cultivation of agropastoralists in Bronze and Iron

Age Inner Asia (3000 BCE - 1000 CE)

by

Melissa M. Ritchey

Doctor of Philosophy in Anthropology

Washington University in St. Louis, 2025

Professor Xinyi Liu, Chair

Professor Michael D. Frachetti, Co-Chair

This dissertation examines the agropastoral practices in the Eurasian landmass between the 3rd millennium BCE to 1st millennium CE, focusing on characterizing how communities living in mountainous Inner Asia incorporated plant cultivation into their mobile agropastoralist lifestyle. I examine macrobotanical remains from key archaeological sites along the routes of the trans-Eurasian exchange of domesticated plants and animals and various technologies during the Bronze and Iron Ages. These sites include Chap, Kyrgyzstan, Tasbas, Kazakhstan, and Dingdong, Piyang, Jiweng, Kaerdong, and Bangga, located in Tibet. I use stable carbon and nitrogen isotope values of archaeological plant remains and macrobotanical assemblages to assess the labor (in the form of watering and manuring) dedicated to plant cultivation. Through this analysis, I investigate whether cultivation strategies travelled with the domesticated crops across the Inner Asian mountains or if these strategies were decoupled from the crops as they moved into new cultural and environmental settings.

Findings indicate that communities developed localized crop management strategies, often taxa specific, rather than adopting a shared cultivation system. While these ancient

communities shared similar crop – and livestock – compositions, they adapted and modified cultivation practices for each of their locales. This research provides insights into the broader implications of agricultural intensification on paleodietary reconstructions, the role of dynamic pastoral systems in shaping agricultural practices, and the localization of agropastoral strategies across Inner Asia. The results show the remarkable flexibility of agropastoralists living at high elevations who incorporated both mobile livestock husbandry and plant cultivation to succeed in sometimes fairly hostile environments for agricultural pursuits. Future research avenues are outlined to further explore the interplay between domesticated plants and animals and their cultural contexts. This work contributes to the understanding of how ancient agropastoral communities navigated the complexities of integrating new agricultural technologies and domesticated species, ultimately transforming both their local environments and the broader Eurasian agrarian and agropastoral history.

Chapter 1:

Introduction

By the 2nd millennium BCE, the underlying structure of the Eurasian domestic food economy was established, featuring post-domestication dispersals of cultivars such as wheat (*Triticum* spp.), barley (*Hordeum vulgare* spp.), broomcorn millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), rice (*Oryza sativa*), and legumes and livestock such as cattle (*Bos taurus*), sheep (*Ovis aries*), goats (*Capra hircus*), horses (*Equus caballus*) and pigs (*Sus scrofa*). This spread connected previously isolated agricultural centers into a trans-continental network of dietary and culinary systems. Novel crops and livestock were introduced into both environments where indigenous agricultural systems were well established and those without. Today, the routes and chronologies of this process are fairly well understood, as I shall unpack below, with extensive scholarly attention drawn to domestication processes in various centers and post-domestication dispersal. The movement of these domesticates across the mountains of Inner Asia – notably the eastern dispersals of wheat and barley and the western movements of the Asian millets – was fundamental to this prehistoric globalization process. The institutional networks of mobile pastoralists that called these mountains home facilitated the spread of ideas, materials, and technologies. However, we currently know little about how these high-altitude nomadic communities strategized to grow domesticated crops and ultimately enabled the transmission of not only crops, but potentially their associated cultivation techniques.

In this dissertation, I investigate how agropastoralists across mountainous Inner Asia incorporated domesticated crops into their subsistence, and by extension, my results reveal how

labor budgets were negotiated in such hybridized subsistence modes. In particular, I explore whether domesticated plants travelled with their technological toolkits across the mountains of Inner Asia or if the Bronze and Iron Ages communities in such environments modified cultivation systems to fit their localized needs. I analyze plant stable isotope values of archaeological remains of domesticated crops and contextualize the results with isotope data of select wild taxa and a broader paleoecology analysis of the macrobotanical assemblage at seven sites across mountainous Inner Asia. These data provide evidence for the labor decisions of Bronze and Iron Age agropastoralists regarding their plant cultivation practices.

1.1 Prehistoric Food Globalization

Between approximately 5000 and 1500 cal. BCE, the movement of several cereal crops and domesticated livestock from distinct domestication centers connected distant communities across the entire Eurasian landmass with a globalized foodway (Jones et al., 2011, 2016b; Liu et al., 2019). As part of this prehistoric *food globalization*, notably, free-threshing wheat (*Triticum* cf. *aestivum/turigidum*) and both naked (*Hordeum vulgare* var. *nudum*) and hulled barley (*H. vulgare* var. *vulgare*) spread from origins in Southwestern Asia, through Inner Asia, and into East Asia (Frachetti et al., 2010; Liu et al., 2017). Much research has focused on the routes and timelines of wheat and barley dispersal (Flad et al., 2010; Frachetti, 2012; Barton and An, 2014; Spengler et al., 2014c; Jones et al., 2016a; Liu et al., 2016a; Zhao, 2018; Motuzaite-Matuzeviciute et al., 2018, 2019b, 2020, 2021b; Deng et al., 2020; Zhou et al., 2020; Tan et al., 2021; Tang et al., 2021) including the possibility of a maritime route in the third millennium BC (Zhao, 2009). During the second millennium BCE, substantial movements across the continent occurred, including the well-documented route of the *Inner Asian Mountain Corridor* (IAMC), a

piedmont zone extending from Southwest Asia through the Pamir, Tianshan, Dzhungar, and Altai Mountains, that connects to the Hexi Corridor (Frachetti, 2012; Liu et al., 2014, 2016a; Spengler, 2015; Stevens et al., 2016; Motuzaite-Matuzeviciute et al., 2019b, 2020; Zhou et al., 2020). The initial spread of wheat and barley cultivation into ancient China likely did not occur simultaneously but through separate processes over millennia via multiple routes, including one traversing the southern Tibetan Plateau (Liu et al. 2017; Lister et al. 2018).

A parallel and contemporaneous transmission of East Asian domesticates of broomcorn and foxtail millet occurred during the 3rd and 2nd millennium BCE. Evidence from macrobotanical remains, stable isotope analysis, paleodietary reconstructions, and, pottery impressions track the arrival of the East Asian millets in Inner and South Asia (Yang et al., 2012; Zhou et al., 2016; Li et al., 2016; Liu et al., 2016b; Spate et al., 2017; Ananyevskaya et al., 2018; Dong et al., 2018; Hermes et al., 2019; Wang et al., 2019; Motuzaite-Matuzeviciute et al., 2022a; Endo et al., 2023; Ma et al., 2023). Notably, there is evidence for a delay in widespread human consumption of millet in the IAMC following its initial dispersal, with newly introduced millets exclusively utilized as livestock fodder in some environments (Hermes et al., 2019). However, other research shows that other IAMC human populations consumed millet in the 3rd millennium BCE, countering previous conceptions of drivers behind millet spread and adoption in Inner Asia (Motuzaite-Matuzeviciute et al., 2022a). Such observations should be further considered in the context of sampling bias and archaeological visibility.

In addition to further refinement of these routes and chronologies, recent research has focused on the various drivers underlying crop movements and implications of adopting foreign resources in novel ecological and socio-cultural environments (Jones et al., 2011; Boivin et al., 2012; Liu and Jones, 2014). Of particular interest are the differences in culinary traditions

between early communities in East and West Asia: in the East, food processing techniques involved boiling and steaming grains, while in the West, grains were ground and baked into flour-based foods (Sakamoto, 1996; Fuller and Rowlands, 2009). These deep-rooted culinary differences partly explain the material distinctions observed archaeologically between East and West Asia. While the Pre-Pottery Neolithic cultures of southwest Asia extensively used querns for flour production and built clay ovens for baking bread and roasting foods, Neolithic and even Paleolithic communities in China used elaborate pottery vessels for a ‘wet-cuisine’ based on boiling and steaming (Fuller and Rowlands, 2011). These East-West culinary differences are deeply embedded in Pleistocene hunter-gatherer food traditions and are intertwined with the domestication process and the transition to agriculture. Further, the East-West differences in food preparation predating domestication partially explain regional distinctions in domesticated taxa, with selections for large-grained (and glutenous) wheat and barley in the grinding-and-baking traditions in the West and small-grained millets for the boiling-and-steaming traditions in the East (Liu and Jones, 2024). Recent research has demonstrated a decoupling of original cooking traditions and associated cereal grains, with foreign grains folded into existing culinary systems as they travelled across Eurasia and the East-West culinary divide (Liu et al., 2016a; Ritchey et al., 2022; Sun et al., 2024).

This decoupling of grains from their associated cooking, and in connection, their ritual and symbolical expressions (Fuller and Rowlands, 2011), has implications for the transmissibility of other cultural institutions associated with domesticated crops and animals. There is a similar disaggregation of livestock management when new domesticated animals were introduced into East Asia. Communities in the Hexi Corridor transformed cattle management into a novel husbandry practice—that was similar to indigenous pig rearing traditions—featuring

an intensive, close management of cattle near the settlements. Sheep and goats, however, were herded extensively, a strategy similar to the pastoralist management of caprines in the IAMC and Southwest Asia (Vaiglova et al., 2021). Interestingly, on the Tibetan Plateau, sheep and goats were intensively provisioned with agricultural by-products and groundwater (Zhang et al., 2024). These nonuniform adaptations of livestock management and crops into new socio-cultural institutions posits further questions regarding the relationship between crops and their cultivation techniques. Do crops and cultivation systems travel together across the IAMC during prehistoric food globalization, or do we see different local permutations of agropastoral labor systems that facilitated the spread of domesticates across Eurasia?

To address this question, I use plant stable isotopes coupled with macrobotanical analyses to assess ancient cultivation techniques. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of archaeological plants allow for the assessment of past growing, specifically the water availability and soil conditions, respectively (Vaiglova et al., 2022; Styring et al., 2024). I focus on the historically less-studied agricultural practices conducted by mobile agropastoral groups to examine their underling labor investment in cultivation. I combine paleoethnobotanical analyses with cereal grain carbon and nitrogen stable isotope analyses from three key locations in the IAMC and western Tibet: Chap I and II in Kyrgyzstan, Tasbas in Kazakhstan, and the Piyang Dongga complex in western Tibet. In the Conclusion, I further contextualize these data with complimentary research I conducted from three additional sites: Koken in Kazakhstan and Bangga in Central Tibet and Kaerdong in Western Tibet (Figure 1). Through this research, I aim to understand the scope of cultivation intensity employed by the earliest known agropastoralists (in these regions).

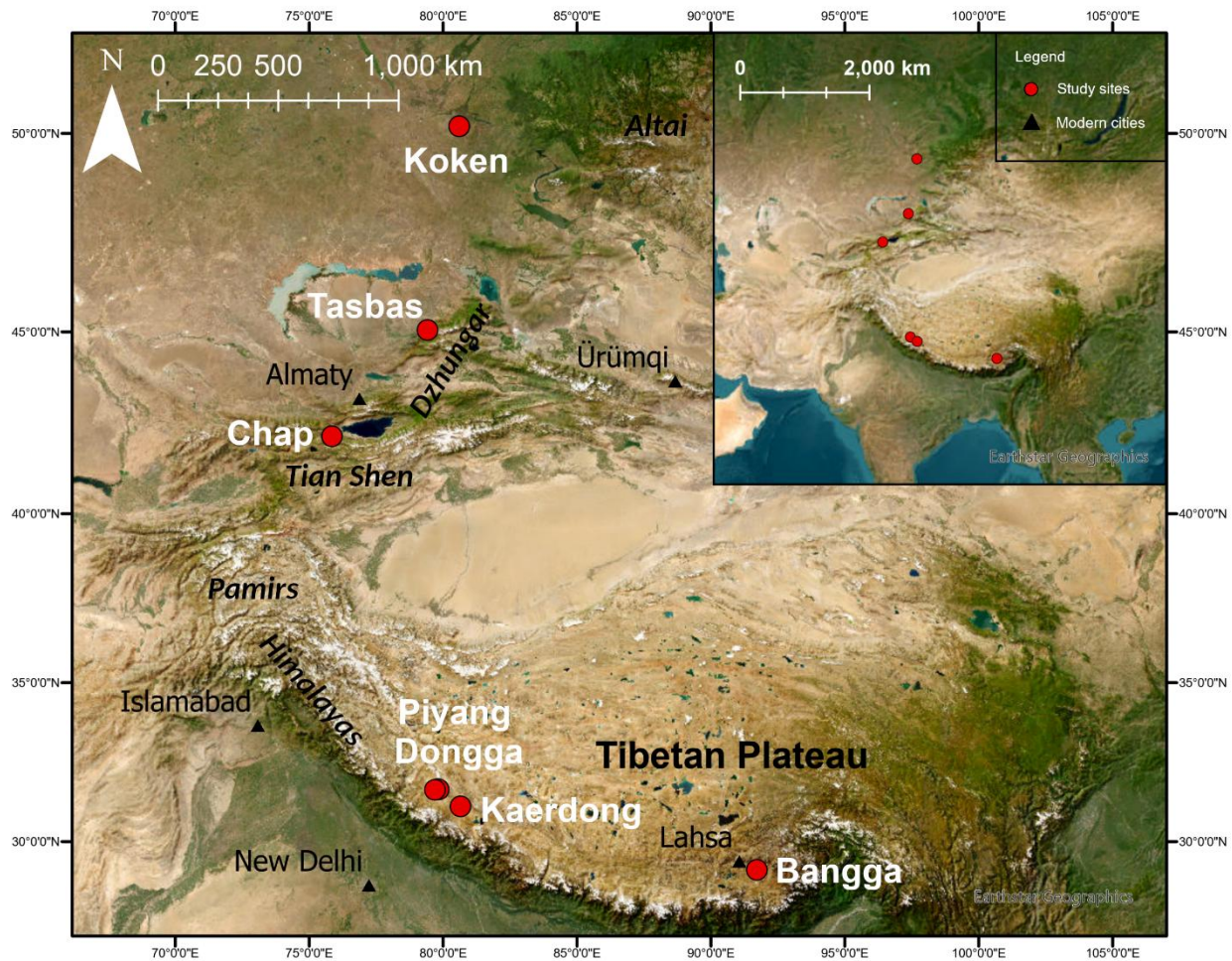


Figure 1. Map of dissertation study sites. Tasbas, Chap, and the Piyang Dongga complex (including Piyang, Jiweng, and Dingdong) are the core study sites. Additional sites I collected data for comparison (and discussed in the conclusion) are shown: Kaerdong, Bangga, and Koken.

I contextualize the results of the plant stable isotope analysis by characterizing the paleoecology from wild taxa present in the macrobotanical assemblages at two of the three case study sites: Chap and Tasbas. Further, I analyzed the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of select arable wild taxa from Chap and Tasbas—the first such research in the study region—to evaluate their potential in inferring field conditions to compliment the crop isotope values. Plant stable isotope analysis is a burgeoning method in archaeological studies, with numerous applications for understanding ancient agricultural systems and paleoclimates in the Levant, Europe, South America, and East Asia (Araus et al., 1999a; Riehl, 2008; Riehl et al., 2008; Lightfoot and

Stevens, 2012; Bogaard et al., 2013, 2016, 2018; Vaiglova et al., 2014a; Girolamo et al., 2014; Styring et al., 2016b, 2017, 2018; Nitsch et al., 2017; Mueller-Bieniek et al., 2019; Szpak and Chiou, 2020; Santana-Sagredo et al., 2021; Gron et al., 2021; Li et al., 2022; Antolín et al., 2024; Joka et al., 2024), but thus far, has had limited application to Central Asian and Tibetan archaeology (Tian et al., 2022; Ritchey et al., 2024). My dissertation is among the first to apply this method to the Bronze and Iron Ages in Inner Asia. Further, by using traditional agricultural theoretical frameworks of labor intensification to understand plant cultivation in mobile agropastoralist communities, I expand the application of this conceptual model. The results of these analyses inform our understanding of localized agricultural adaptation in landscapes that are traditionally viewed as the realm of mobile pastoralists. My results further enable more holistic interpretations of isotopic paleodiet reconstructions using human and faunal remains in these environments. The choices made by herders or farmers are more than utilitarian and are often bound by symbolic and cultural values embodied in given social institutions. By investigating the material and ecological ramifications of these cultivation choices, this project connects with central issues in anthropological archaeology with regards to the cultural use of food, stability, interaction, and agency (Sahlins, 1976; Goody, 1982; Netting, 1986; Sherratt, 1995; Douglas, 2003).

In the remainder of this chapter, I provide the theoretical and methodological frameworks for plant stable isotopes in archaeological research to investigate ancient labor and cultivation strategies. I also present regional and site-specific information regarding the case studies in each of the following chapters. I conclude with a description of the organization of this dissertation.

1.2 Grains as Proxies for Labor Strategies

The successful integration of agriculture into pastoralist lifeways in mountainous Inner Asia facilitated the transmission of domesticated crops and animals across Eurasia between the 3rd and 1st millennia BCE. Characterizing the labor negotiations for this integration is key for understanding both the local, site-based social institutions and the broader, regional processes of *prehistoric food globalization*. For a mixed agropastoral economy, labor would need to be negotiated between cultivation and other tasks, particularly the management of livestock herds. At least for a portion of the population, mobility in livestock herding would place strains on the labor requirements needed for crop management (Lees and Bates, 1974). Agropastoral communities would need to negotiate both punctuated and continuous requirements of irrigation, tilling, manuring, and weeding with those of the livestock, such as access to pasture and water, culling, and breeding. The requirements of each system – cultivation and herding – are potentially opposed but were successfully combined in the agropastoral economies of mountainous Inner Asia.

Central to this inquiry is the tension between relatively low labor input per area unit (however, offset by extensiveness) in extensive pastoral activities and the potentially intensive requirements (high labor input per area unit) of plant cultivation in less-than optimal agricultural environments (Boserup, 1965; Vainshtein, 1980; Khazanov, 1983). Pastoral economies utilize extensive labor practices, where the bounds of production are not limited by land but by the ability to convert those expanses of land into usable resources through animal husbandry (Boserup, 1965; Khazanov, 1983; Barfield, 1999). Productivity is driven by the size of animal herds, ecological feedback from herds maintaining grassland, and the accessibility to and quality of grassland. Risks are mitigated through herd and grazing land management (Vainshtein, 1980,

pp. 60–61; Khazanov, 1983; Gursan-Salzmann, 2005; Chang, 2015; Kradin, 2015). Agricultural economies, on the other hand, are often more constrained by land availability when compared to pastoral systems. In the classic *Boserupian* perspective (1965), productivity is driven by labor input per unit area to gain higher yields in spatially confined farming environment, often due to ecological or political constraints. Increase in labor investment for activities such as irrigation, ploughing, field management, harvesting improvement and crop processing enables potential food surpluses, which buffers against future resource shortages – either through direct resource use or via trade/exchange (Boserup, 1965; Halstead, 1989, 1990; Halstead and O’Shea, 1989). Livestock herding and crop management can be combined to compliment the labor requirements for each system, as proposed by Bogaard (2005) for Neolithic Europe; extensive herding is often complimented by similarly extensive plant cultivation strategies. When these two systems were integrated through prehistoric food globalization processes, as attested archaeologically in mountainous Inner Asia, how did agropastoralists reconfigure the extensive pastoral and intensive agricultural systems with distinct labor requirements to form a coherent social system?

Ethnographic studies show how contemporary agropastoralists use a range of intervention and improvement strategies that can be traced in the archaeological record: irrigation, manuring, and weeding. Some agropastoralists practice dryland agriculture by planting cereals near waterways in highland pastures that were loosely managed and then harvested as fodder for their herds (Vainshtein, 1980; Di Cosmo, 1994; Soucek, 2000, p. 3). Others participate fairly heavily in agricultural pursuits, dividing labor and time among family to manage crops and livestock, with heavy usage of irrigation, manure, and multi-cropping to improve yield (Kradin, 1963, pp. 24–25; Vainshtein, 1980; Khazanov, 1983, pp. 34–35). Nomadic pastoralists in Tuva, Siberia, for example, grew millet and barley to supplement their pastoralism, aligning sowing and

harvesting times with movement to spring and autumn pastures, sometimes with men visiting the barley fields through the summer to manage the fields and repair gravity-fed irrigation channels. However, they did not manure or weed their fields (Vainshtein, 1980, pp. 89–90; 148–151). Researchers have hypothesized that cultivation in nomadic communities, if conducted, played a secondary, supplementary role, characterized by extensive, low-investment agriculture to supplement fodder for livestock and human consumption (Khazanov, 1978, 1983; Di Cosmo, 1994; Spengler, 2013, p. 28). To assess the role of agriculture in Bronze and Iron age agropastoral communities, I use stable isotope analysis complimented by an analyses of wild seed assemblages as proxies for labor investment into plant cultivation.

1.3 Plant Stable Isotope Principles

Stable isotope analyses of archaeological plant remains provide information regarding the plants' growing conditions. $\delta^{13}\text{C}$ values infer water availability during growth (Farquhar et al., 1989; Stewart et al., 1995; Araus et al., 1997, 1999a; Wallace et al., 2013). $\delta^{15}\text{N}$ values allow for the assessment of soil ^{15}N enrichment or depletion during plant growth, which infer cultivation strategies (Bogaard et al., 2007; Fraser et al., 2011; Styring et al., 2018). Both natural and human activities can influence plant stable isotopic compositions and numerous experiments provide baseline frameworks for interpreting the role of anthropogenic activities in ancient agricultural systems (see following discussion). Together, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values allow for the assessment of ancient strategies of water and soil maintenance, shedding light on early agricultural management in Southwest Asia, Europe, East Asia (Ferrio et al., 2005; Aguilera et al., 2008, 2018; Bogaard et al., 2013; Araus et al., 2014; Vaiglova et al., 2014a; Styring et al., 2016b; Treasure et al., 2019; Li et al., 2022) and recently in Inner Asia (Tian et al., 2022; Ritchey et al.,

2024). In the following section, I explain underlying mechanisms of using $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values to understand ancient growing conditions.

$\delta^{13}\text{C}$ values of plant remains measure the fractionation of carbon during photosynthesis, which is impacted by water-availability, among other factors. Plants with different photosynthetic pathways are classified into three groups: C_3 , C_4 and CAM plants. For my research, only C_3 and C_4 photosynthetic pathways apply as CAM plant contribute little to human and animal foodways in Inner Asian environments. In C_3 plants, the enzyme Ribulose-1.5-bisphosphate carboxylase/oxygenase (RuBisCo), found in mesophyll cells, fixes atmospheric CO_2 . By contrast, in a more efficient carbon fixation pathway, C_4 plants use mesophyll cells to fix CO_2 with the enzyme phosphoenolpyruvate (PEP) carboxylase into a four-carbon compound that is then transported to bundle-sheath cells where the CO_2 is refixed by RuBisCo. In both pathways, the ratio of intercellular ambient partial pressure of CO_2 , temperature, and leakiness of the bundle-sheath cells can all impact the final photosynthetic product (Farquhar et al., 1989). During photosynthesis, both C_3 and C_4 plants assimilate two forms of carbon isotope, the lighter ^{12}C and heavier ^{13}C . However, C_4 plants discriminate the heavier carbon isotope, ^{13}C , less than C_3 plants during the process, resulting in higher $\delta^{13}\text{C}$ ratios in plant tissue.

For C_3 plants, it is well established that water availability directly influences the plant's ability to assimilate CO_2 due to stomata conductance – pores on leaves that continuously open and close to allow for photosynthesis to occur (Farquhar and Sharkey, 1982; Cernusak et al., 2013). When water is plentiful, CO_2 moves through the open leaf stomata relatively freely, resulting in preferential assimilation of the lighter $^{12}\text{CO}_2$ over the heavier $^{13}\text{CO}_2$. When water is limited, however, plants will periodically close the stomata to preserve moisture (which transpires through these pores along with CO_2). This causes CO_2 to recycle, resulting in

relatively less discrimination of heavier $^{13}\text{CO}_2$ (O’Leary, 1988; Girolamo et al., 2014). The ratio between ^{12}C and ^{13}C , expressed as $\delta^{13}\text{C}$, is therefore informative about water availability during plant growth. A more negative $\delta^{13}\text{C}$ value reflects higher water use efficiency during the grain-filling period (Farquhar et al., 1989; Araus et al., 1997; Wallace et al., 2013). Water availability reflects different forms of input, including anthropogenic watering, rainfall, ground-water flow, water losses from evaporation or evapotranspiration, and the soil’s ability to hold water (Wallace et al., 2013). When analyzing samples from arid paleoenvironments, interpreting anthropogenic watering from $\delta^{13}\text{C}$ values is fairly straightforward (see below). In more mesic environments, such as the site of Tasbas, natural water sources, need to be considered (Stewart et al., 1995; Swap et al., 2004).

When measuring archaeological grains, we are often comparing data from different temporal periods (when the isotope composition of atmospheric CO_2 differed). Therefore, we must make a conversion of the results to account for diachronic changes in $\delta^{13}\text{C}$ values of atmospheric CO_2 . $\Delta^{13}\text{C}_{\text{plant-air}}$ captures the amount a plant discriminated against ^{13}C regardless of the source CO_2 in the atmosphere. I calculated $\Delta^{13}\text{C}_{\text{plant-air}}$ ($\Delta^{13}\text{C}$ hereafter) with the equation developed by Farquhar et al. (1989):

$$\Delta^{13}\text{C} = \frac{\delta^{13}\text{C}_{\text{air}} - \delta^{13}\text{C}_{\text{plant}}}{1 + \delta^{13}\text{C}_{\text{plant}}}.$$

I use a $\delta^{13}\text{C}_{\text{air}}$ value of - 6.5 ‰ inferred by Ferrio et al. (2005) from ice cores records, for the Bronze and Iron Ages (3500 – 2300 BCE). Once converted to $\Delta^{13}\text{C}$ values, the directionality of inferred water availability reverses, with higher $\Delta^{13}\text{C}$ values corresponding to wetter soils. This conversion allows us to compare archaeological materials across different time periods and to values from modern growing experiments. Experiments in arid locations, such as the Mediterranean and Southwest Asia, estimate the effect of irrigation on carbon isotope

fractionation in common crops (Araus and Buxo, 1993; Araus et al., 1997, 1999a, 1999b, 2003; Wallace et al., 2013). Wallace et al. (2013) established watering thresholds for interpreting $\Delta^{13}\text{C}$ values from archaeological wheat, barley, and lentils from irrigation experiments, including dry, unirrigated fields. Li et al. (2022) compliments this work with a numeric boundary for Wallace et al. (2013)'s original watering threshold gradient, where values below the Optimal Watering Threshold (OWT), suggest water availability limited plant growth, values above the OWT suggest water regimes that did not limit plant growth and values above the Superfluous Watering Threshold (SWT) suggest regimes that provided abundant water beyond the plants' needs. Ferrio et al. (2005) modelled water inputs from $\delta^{13}\text{C}$ values of modern rainfed and irrigated bread wheat, barley, and faba beans for comparison to archaeological grains. Taxa can have different carbon assimilations under the same growing conditions, such that similar $\Delta^{13}\text{C}$ values will reflect different stress (or non-stress) levels depending on taxa. Wallace et al. (2013) and Li et al. (2022)'s thresholds take this differential assimilation into account and provide an interpretive framework for common domesticated crops.

Additional natural factors can influence the $\Delta^{13}\text{C}$ values of C_3 plants. Atmospheric pressure at high elevations reduces carbon discrimination, therefore increasing $\delta^{13}\text{C}$ (and subsequently decreasing calculated $\Delta^{13}\text{C}$ values) in the plants (Zhou et al., 2011; Szpak et al., 2013). Szpak et al. (2013) find a positive linear correlation with elevation and $\delta^{13}\text{C}$ values in Peruvian C_3 plants ranging from lowland (approximately 10 masl) to highland (>4000 masl) areas (Spearman's $r = 0.879$, $p = 0.001$). There is a positive offset of approximately 2 – 5 ‰ between values from the lowest elevation plants and those at the highest. These findings correlate with those on the Tibetan Plateau, where there is a mean positive increase of 1 – 2 ‰ across a variety of C_3 plants between 2500 – 5500 masl (Zhou et al., 2011). Thus, to

accommodate for the atmospheric pressure influence on $\delta^{13}\text{C}$ values on the plant remains from sites on the Tibetan Plateau (>4000 masl), I adjust the calculated $\delta^{13}\text{C}$ ratios for watering bands by a conservative average of $+2$ ‰ difference.

While $\delta^{13}\text{C}$ values are used to infer water availability, $\delta^{15}\text{N}$ of plants reflect the isotopic compositions of the nitrogen ($^{14}\text{N}/^{15}\text{N}$) sources. For N non-fixing plant species, such as cereals, nitrogen is primarily incorporated from the soil. Natural and anthropogenic processes both contribute to soil N influencing the $\delta^{15}\text{N}$ values of plants (Ambrose, 1991; Bogaard et al., 2007; Fraser et al., 2011; Girolamo et al., 2014; Szpak, 2014). There are a number of natural causes that can elevate soil $\delta^{15}\text{N}$ values, including soil salinity, aridity, and denitrification (Virginia and Delwiche, 1982; Heaton, 1987; Hastorf, 1988; Farrell et al., 1996; Nazarea, 2006; Hartman, 2011; Szpak, 2014; Styring et al., 2015). Anthropogenic actions, such as manuring of fields, will greatly increase $\delta^{15}\text{N}$ values (Szpak, 2014). This is due to ammonia volatilization, a process by which ammonia gas is transformed from ammonium, resulting in net loss of soil nitrogen and counting for 30-60% of the global nitrogen cycle (Szpak, 2014). Significant nitrogen isotope fractionation occurs during this process. Modern experiments show that manure application to crop fields substantially increase $\delta^{15}\text{N}$ values above of that of the natural baselevel, with values above 6‰ in the European and Southwest Asian contexts when intensive manuring is applied (Bogaard et al., 2007, 2013; Fraser et al., 2011). Cumulative, long-term manuring has the most impact of $\delta^{15}\text{N}$ values in crops (Fraser et al., 2011; Kanstrup et al., 2011a). However, as the soil N cycle is extremely complex and numerous naturally occurring effects could alter soil $\delta^{15}\text{N}$ values significantly, analytical sensibility is required to interpret $\delta^{15}\text{N}$ values isotopically measured from charred botanical remains.

A way to account for ancient natural N sources is by estimating the natural baselevel of $\delta^{15}\text{N}$ values of wild vegetation in a given environment (Vaiglova et al., 2022). This is done primarily through measuring the $\delta^{15}\text{N}$ values of archaeological remains of wild herbivores, which subsisted largely on natural vegetation, recovered from the site or surrounding areas. There is a known N trophic level offset of approximately 3-5 ‰ between diet and consumer tissues, such that herbivore tissues are 3-5 ‰ higher than the values of their vegetative diet (DeNiro and Epstein, 1981; Minagawa and Wada, 1984). We assume that wild herbivores did not regularly consume plants from anthropogenically modified landscapes, but they could have raided tended fields. Further, wild herbivores may travel vast distances, consuming plants from a variety of soil environments with differing $\delta^{15}\text{N}$ values. This could complicate the assessment of a local baselevel from these herbivores as they may not necessarily represent the specific, local, nitrogen environment of the natural landscape where cultivation was conducted. However, using $\delta^{15}\text{N}$ values of archaeological low-level herbivores is currently our best method of gaining a picture of the N environment around a site during its occupation, as other methods – such as analyzing $\delta^{15}\text{N}$ values of wild archaeological plant remains or archaeological soils – have other complicating factors, including taphonomic processes and nitrogen leaching and/or hotspots (Szpak, 2014; Vaiglova et al., 2022; Styring et al., 2024). With these assumptions considered, we can infer a natural range for $\delta^{15}\text{N}$ values to compare the results of the archaeological plant remains. Archaeological plant $\delta^{15}\text{N}$ values measuring substantially above this natural baselevel can then be considered as anthropogenically sourced. Each site in my study is located in different environmental and ecological systems, both in terms of geographies and climates, necessitating the estimation of a baselevel for each site. Thus, I calculated a natural N baselevel from available $\delta^{15}\text{N}$ values of archaeological fauna from each site or nearby contemporary sites, preferentially

selecting values from fauna identified as wild herbivores, but when not available, selecting herbivores with low $\delta^{15}\text{N}$ values (as done in Chapter 2 for the Chap case study).

In addition to understanding natural and anthropogenic influences, it is important to consider taphonomic effects on isotopic values. The archaeological seeds I analyzed are charred from exposure to high temperatures and possibly directly to fire which chemically altered the seeds by removing water vapor and volatile organics. Overall, the seed maintains its carbon and nitrogen values through this charring process, albeit with known offsets which varies with the temperature and duration of charring. The average calculated isotopic offset in cereal grains (rye, sorghum, wheat, barley, oats, and pearl millets) is $\sim 0.2\text{‰}$ for $\delta^{13}\text{C}$ and $\sim 0.3\text{‰}$ for $\delta^{15}\text{N}$ (Nitsch et al., 2015; Styring et al., 2019, 2024; Stroud et al., 2023a; Varalli et al., 2023). For broomcorn and foxtail millet, Stroud et al. (2024) estimate a $\delta^{13}\text{C}$ offset of $\pm 0.16\text{‰}$ and a $\delta^{15}\text{N}$ offset of $+0.94\text{‰}$, with more negative $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in husked grains than in naked grains. These are lower than the conservative 1‰ uncertainty used in many paleodietary studies (Fraser et al., 2013) and thus should have little impact on data interpretation. However, it is still important to consider the potential charring effect, especially when reconstructing past agricultural practices in comparison to modern isotopic experiments.

1.4 The Inner Asian Mountain Corridor and the Trans-Eurasian exchange

The sites chosen for this dissertation represent key locations along the broadly delineated Inner Asian Mountain Corridor (IAMC), where Bronze Age communities are theorized to be connected through nonuniform institutional interactions that allowed for the movement of beliefs, technologies, people, cultures and their plant and animal domesticates cross the highland valleys and ridges of the Tian Shan, Dzhungar, Altai, Hindu Kush, Kopet Dag, Pamir, and

western Himalayan Mountains that bisect the Eurasia continent (Frachetti, 2012; Spengler, 2015). Agropastoral activities tied these communities together but manifested in unique ways regionally and at each site, in a formation processes Frachetti (2012) calls nonuniform institutional complexity. Significantly, between the 3rd and 1st millennium BCE, these communities used the mountains as conduits for spreading Southwest Asian domesticates, like wheat, barley, peas, sheep, goats, hors, and cattle, north and eastward into ancient China and East Asian domesticates, like broomcorn and foxtail millet, westward into Central Asia and potentially beyond to Europe (Frachetti et al., 2010; Spengler et al., 2014c; Motuzaite-Matuzeviciute et al., 2015, 2017, 2019b; Liu et al., 2019; Zhou et al., 2020). Their unique adoptions of livestock herding and plant cultivation, coupled with an interconnected material culture tradition in the mountainous regions of Inner Asia, provide a case study for understanding local manifestations of labor organization, identity, and social structure. A key, under researched component of this is the particular agricultural strategies employed at each site: did agropastoralists at Chap, Tasbas, and the Piyang Dongga Complex adopt similar management systems for the foreign crops, indicating coupled movements of crops and cultivation strategies, or did they modify these strategies to better fit an agropastoral lifestyle in mountainous Inner Asia? In this dissertation, I address this question by analyzing proxies for labor investment in cereal crops through plant stable isotope analyses of cultivated crops and associated wild taxa at various sites across the broader IAMC.

1.5 Stable Isotope Analyses in the IAMC

The growing field of stable isotopes on archaeological material in the IAMC has played a crucial role in shaping our understanding of these interconnected communities. By examining the isotopic signatures of human and animal remains, these studies have elucidated patterns of diet,

migration, and herding practices that are essential for contextualizing the broader strategies employed across the region. In this section, I provide a review of the previous research on stable isotope analyses in the study area to contextualize my research on the plant side of the story, which provides a key missing link in discussing ancient foodways and labor organization. Across Inner Asia, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values have been used to trace the emergence of pastoralism and shifts in practice (O’Connell et al., 2003; Motuzaite-Matuzeviciute et al., 2015, 2016, 2022a; Hermes et al., 2019). Using $\delta^{13}\text{C}$ of humans and domestic livestock, researchers have traced the emergence and diversity of millet consumption and cultivation during the 3rd – 2nd millennium BCE in the IAMC (Liu et al., 2016b; Hermes et al., 2019, 2022; Motuzaite-Matuzeviciute et al., 2022a) and the diversity of paleodiets along the Medieval (*ca* 2nd – 16th c. CE) Silk Roads (Hermes et al., 2018). For example, in the Dzhungar Mountains of Southeastern Kazakhstan, *ca* 2500-2300 BCE, analyses reveal intensive management of sheep, goats, and cattle with millet foddering (Hermes et al., 2019). In the Tien Shan of Kyrgyzstan during the 3rd millennium BCE, both humans and their domesticated livestock consumed a diet predominately of C₃ grasses, with some unique cases of C₄ millet consumption (Motuzaite-Matuzeviciute et al., 2022a). Millet cultivation and consumption increased from the Final Bronze Age to Iron Ages between 1300 – 800 BCE, followed by a return to an emphasis on nomadic pastoralism as seen through a dip in C₄ plant consumption and a greater reliance on animal products reflected in increased $\delta^{15}\text{N}$ values (Motuzaite-Matuzeviciute et al., 2022a).

Using $\delta^{18}\text{O}$ values, researchers have traced transhumance practices to further investigate mobile pastoralism and livestock seasonality (Hermes et al., 2022; Zhang et al., 2024). In the Eastern Tian Shan and beyond into the Hexi Corridor, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotopes of Bronze Age (3rd- 2nd millennium BCE) humans and animals reveal differing management of cattle and

sheep/goats and the importance of animal products in human diets (Vaiglova et al., 2021). There is further variation in C₃ and C₄ plant consumption between the 3rd and 1st millennium BCE (Ling et al., 2013, 2016; Liu and Reid, 2020). The use of stable isotopes on archaeological plant material remains limited in Inner Asia. In the Eastern Tianshan, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of domesticate cereals from 1300 BCE to 300 CE indicate increasing pastoralism and less investment in plant cultivation (Tian et al., 2022). These previous studies underscore the importance of stable isotope analysis in unraveling the complexity of past agropastoral and dietary practices. I add to this growing literature by analyzing the nature of cereal cultivation by agropastoralists in the IAMC and the Tibetan Plateau, two key regions for the spread of plant domesticates across Eurasia in prehistory. My research results have profound implications for not only understanding ancient agricultural strategies but also for how we interpret dietary analyses using stable isotope data of associated humans and animals (Vaiglova et al., 2022).

1.6 Site Specific Information

1.6.1 Chap I and II

The Chap sites (42° 10'51.7" N, 75°51'3.64" E) are in Kochkor Valley of the central Tien Shan Mountains, Kyrgyzstan at 2000 meters above sea level (masl hereafter). The sites are near a natural snowmelt-fed spring on a south-facing slope of foothills in the southeast of the valley. Today, the valley has a unique microclimate that is favorable to year-round agropastoralism with mild annual temperatures and exposed bedrock that stores solar energy that prevents winter snow accumulation (Chupakhin, 1959). However, the steep surrounding mountains receive more intense weather, with south-facing slopes often experiencing snowstorms in the summer, preventing successful cereal cultivation above 2600 masl. Farming is currently concentrated in

the valley floor utilizing terraced and stream irrigated systems, as the surrounding hillsides steeply increase in elevation. The valley also comprises alluvial river fans, large salt outcrops, arid steppe vegetated mountain slopes and rich pastures on plateaus. (Motuzaite-Matuzeviciute et al., 2019b, 2020, 2021b, 2022b). Modern precipitation averages 200 mm/year with maximum rainfall during July and 80% of rainfall occurring between May and September (Chupakhin, 1959; Böckel and Becker, 2014). There are, however, elevated evaporation rates which maintain a relatively dry local climate. As such, the sparse vegetation is dominated by arid steppe grasses and shrubs such as *artemisia* spp. and *stipa* spp, with larger vegetation concentrated along seasonal waterways and drainages (Kasymov, 2015; Rouse et al., 2022). This dryer climate requires water management for successful cultivation, evidenced through ancient irrigation features spread all over the area and modern-day irrigation ditches (*aryks*) and canals in the valley floor (Rouse et al., 2022).

The Kochkor valley has a deep archaeological history, likely due in part to the valley's hospitable climate, even at 1800-2000 masl. Evidence of Middle-and Upper Paleolithic, Bronze and Iron Ages, and historic Silk Road Karakhanid sites are present in the region (Amanbayeva et al., 2011; Abdykanova, 2014; Ivanov, 2017; Motuzaite-Matuzeviciute et al., 2021b, 2022b). Aerial and pedestrian surveys show an abundance of undocumented sites present, indicating rich occupation of the valley in the past (Rouse et al., 2022). Petroglyph, ceramic, and subsistence evidence show connections to broader Inner Asia during the Bronze and Iron Ages and Silk Road periods (Kuz'mina, 1986; Ivanov, 2017; Motuzaite-Matuzeviciute et al., 2022b).

Chap was discovered in 1992 by K. Sh. Tabaldiev during the excavation of a Turkic period burial mound atop the Chap site location. Subsequent excavations in 2011, 2015-2021, led by G. Motuzaite Matuzeviciute and A. Abdykanova uncovered the remains of Chap I and Chap

II. Chap I and II are two distinct occupation events that have evidence of multiple domestic layers including fireplaces, ovens, burial pits, domestic pits and floors, and structural features. Abundant faunal and floral remains show evidence of highland pastoralism and agricultural activities. Bayesian statistics model the Chap I farmstead occupation from 1102-926 cal BCE to 916-816 cal BCE. Below approximately 1 meter of sterile soil, lies an extensive earlier occupation horizon, Chap II. Occupation at Chap II occurred between 2474 – 2162 cal BCE (Motuzaite-Matuzeviciute et al., 2022b). The abundance of domesticated cereal crops, crop processing byproducts, pastoral faunal remains, and certain ceramic styles indicate an agropastoral occupation, where at least some of the community remained sedentary to manage possibly spring- and autumn- sown crops, beginning in the 3rd millennium BCE and continuing in the 2nd to 1st millennium BCE (Motuzaite-Matuzeviciute et al., 2020, 2021b, 2022b). Zooarchaeological and ZooMS analyses of Chap I point to a higher reliance on sheep/goats than cattle than Chap II. Further, a high survival of older animals and a preference towards sheep over goats suggests a selection for secondary products, such as milk and wool (Ananyevskaya et al., 2021). Unmanned Aerial Vehicles (UAV) photogrammetry, geophysical surveys, and subsequent analyses in the surrounding area show a long-term, heavily managed landscape including irrigation ditches, altered natural waterways, check dams and diversion walls, catchment areas, and terraces (Rouse et al., 2022).

1.6.2 Tasbas

The site of Tasbas (1492 masl, 45.13427 N, 079.36794 E) sits between large granite boulders and a seasonal stream, along a southward slope that faces the Dzhungar Alatau in the Koksu River Valley of Semirech'ye, Kazakhstan. Diverse ecologies span different altitudes, with arid steppe regions about 100 km west of the mountains transitioning into shrubby forests in the

foothills and alluvium of the Dzhungar, expansive piedmont and rich pastures around 3500 masl, bordered by evergreen forest on the northern slopes of the mountains (Spengler, 2013; Hermes et al., 2021). The region receives ~ 500 – 1200 mm of annual rainfall dependent on elevation and aspect (Frachetti, 2008, p. 85) and spring snowmelt and runoff from glaciers supply water to the valley floor (Spengler, 2013; Hermes et al., 2021). Temperatures range from warm summers to freezing winters and are also affected by elevation, with decreasing mean annual temperatures the higher the elevation. Below 800 masl there is less snow cover, while above 1000 masl, a lot of snow accumulates in the winter. In these higher elevations, daily temperatures also fluctuate greatly (Goloskokov, 1984; Spengler, 2013; Hermes et al., 2021).

The first pilot excavations in 2001 were led by the Institute of Archaeology in Almaty, Kazakhstan, and identified evidence for Bronze Age and Kazakh period occupation (Mar'yashev, 2002). Following survey and excavations in 2002, 2005, 2006, and 2009-2011, as part of the Dzhungar Mountain Archaeological Project (DMAP), identified similar Bronze Age occupation layers, cemetery complexes, and abundant petroglyphs in the region around Tasbas and the neighboring site of Begash and Dali (Mar'yashev, 2002; Frachetti and Mar'yashev, 2007; Baipakov and Mar'Yashev, 2008; Spengler et al., 2014c; Doumani et al., 2015; Hermes et al., 2021).

Comprehensive data collection and analysis of ceramics, lithics, fauna, flora, and phytoliths from Tasbas show evidence for early ritual activity, followed by a mixed mobile pastoralist economy that integrated agriculture to support a multi-season residence (Doumani et al., 2015). Radiocarbon dates and ceramic typologies show multiple occupation periods at Tasbas that span 5000 years, from the 3rd BCE to 1st millennium CE. The 2011 excavations revealed both ritual and domestic architecture, including a cremation cist, domestic hearths and

trash pits, an outdoor activity area, and encampment without a foundation. Cementum analysis of faunal remains indicates a year-round occupation (Schmaus et al., 2019). Domestic livestock dominates faunal remains (92 % of assemblage), including sheep/goats (*Ovis/Capra*), cattle (*Bos taurus*), horse (*Equus*), ass (*Equus asinus*), and camels (*Camelus*). Analysis of the ceramic assemblage, including digital radiographs, compositional analysis using neutron activation for provenance, and textile impression, shows a local, hand-made tradition utilizing slab-coil or slam-mold construction, with some ceramics showing evidence of textile-line molds (Doumani and Frachetti, 2012; Doumani et al., 2015). The ceramic production technique remains remarkably stable through the occupation layers, with some changes in vessel ornamentation through time. The macrobotanical remains revealed Early Bronze Age ritual use of wheat at Tasbas, followed by evidence of local cultivation of predominately barley, with some wheat, peas, and millet in the 2nd millennium BCE (Spengler et al., 2014c, 2014b; Doumani et al., 2015).

Nearby, approximately 300 meters to the west, excavations at the site of Dali found a similar Bronze Age pastoralist economy with abundant domestic faunal remains, dated to 2845-970 cal. BCE (Hermes et al., 2021). However, no domesticated crops and scant wild taxa were recovered from flotation. Additionally, the Tasbas assemblage matches closely with those recovered from the site of Begash (950 masl), roughly 1000 meters southwest along the riverine terrace. Begash has a 4000-year occupation history, 2460 cal. BCE – 1950 cal. CE, and includes both domestic architecture, smaller encampments, and cemetery contexts, including an Early Bronze Age cremation cist, Late Bronze Age stone cist burials and Iron Age Kurgans (Frachetti and Mar'yashev, 2007; Frachetti and Benecke, 2009). From the Early Bronze Age (ca. 2500 BCE), subsistence at Begash relied primarily on domestic livestock herding and wild game

(primarily red deer (*Cervus elaphus*) and goitered gazelle (*Gazella subgutturosa*)), with increased reliance on a livestock husbandry from ca. 2000 BCE onward, including mostly sheep, cattle, and some horse and camel. Artifacts include ceramics, stone tools (grinders, micro-blades, cores, and hammerstones), and spindle whorls. Through time, there is a change in ceramic technology, paralleled by a decrease in stone tool use and adoption of bronze technology by the 2nd millennium BCE (Frachetti and Mar'yashev, 2007). The Early (970 – 400 cal. BCE) and Late Iron Ages (cal. CE. 70-500) have evidence of Saka and Wusun Period occupation and burials, respectively.

Initially interpreted as a seasonal pastoralist campsite, subsequent analysis of flotation samples identified evidence of domesticated crop use at Begash. From the first phase of occupation, ca. 1500 - 1950 cal. BCE, 13 wheat, 61 broomcorn millet, and 1 barley grains were recovered from a cremation burial cist and associated funerary fire-pit (Frachetti et al., 2010; Spengler et al., 2014c). The later occupation layers contained some wheat and broomcorn and foxtail millet (Spengler, 2013; Spengler et al., 2014c). No evidence of local processing of domesticated crops from the macrobotanical remains was identified at Begash, but impressions in ceramics from the early Bronze Age contexts contain broomcorn and foxtail impressions (Endo et al., 2023). Further, stable isotope analyses of faunal remains from Begash and Dali/Tasbas indicate high consumptions of C₄ crops – millets – and nitrogen enriched fodder, suggesting at least regional access to cultivated millet fodder and an agropastoral economy at Begash, Dali, and Tasbas (Hermes et al., 2019).

In 2023, the team returned to Tasbas to expand the excavation areas from the previous field seasons and identify early occupation layers. These new occupation horizons contained domestic activities, structural materials, fireplaces/burning events, and human burials. Chapter 4

reports on my analyses of the macrobotanical remains from the 2023 excavation and the stable isotope analysis of plant remains from both 2011 and 2023.

1.6.3 Piyang Dongga Complex

Along a tributary of the Langqên Zangbo (Upper Sutlej River) in Zhada County, Ngari prefecture in the western Tibet Plateau, are a group of sites called the Piyang Dongga complex. Located within the Plateau temperate monsoon climate zone, the region has a mean annual precipitation of less than 450 mm/year and cooler average temperatures than the eastern and central Tibetan Plateau (Tang et al., 2022). Today, the region comprises only one percent of Tibet's total cropland, with arable land limited by poor soil nutrition and restrictive landscapes (Du, 2003; Tang et al., 2022). The Piyang Dongga complex include the sites of Dingdong (4212 masl), Piyang (4174 masl), and Jiweng (4094 masl). The complex comprises several prehistoric settlements, cemeteries, and historic Buddhist monuments (Fu, 2008; Lu, 2008; Tang et al., 2022). Faunal remains of sheep/goats, yaks/cattle, and horses indicate long-term pastoral activities in the site area (Lu, 2008). Excavations in 2019 uncovered new evidence of occupation and agropastoral activities at the sites, coinciding with an agriculture system focused on 6-row barley cultivation (Tang et al., 2022). Evidence of likely local cultivation is clear through the abundant remains of grains, rachises, and culm nodes, indicating crop processing.

Dingdong is a collection of eleven stone structures and three semi-subterranean houses that represent a year-round agropastoral village (~150m²), occupied between 348 cal BCE to 541 CE (Tang et al., 2022). Macrobotanical remains include naked barley, hulled barley and barley rachises (Tang et al., 2022). Jiweng is a large stone enclosure (~960m²), occupied between 391 – 208 cal BCE. A small test excavation of three trenches recovered only one artifact, an almost complete red-sand pot, and abundant macrobotanical remains. The layout and lack of artifacts

recovered is similar to historical seasonal campsites in the region and suggest a seasonal agropastoral campsite. Evidence of naked and hulled barley cultivation were recovered (Tang et al., 2022). During construction in the village of Piyang, a soil section was exposed containing abundant ceramics, animal remains, and charcoal. Researchers sampled three subsections with dense deposits for floatation. Due to the rescue nature of this sampling, it is unclear the site type of the archaeological deposits at Piyang, dated to 396-212 cal. BC, but a similar assemblage indicating local barley cultivation was identified (Tang et al., 2022).

1.7 Dissertation Organization

This dissertation is organized based upon the three-article model, wherein each data-presenting chapter consists of a published or publishable stand-alone article that articulates with my overarching research question. Each chapter includes its respective bibliography. In Chapter 2, I present plant stable isotope research of wheat, barley, and wild taxa from the site of Chap, in the Tien Shen Mountains of Kyrgyzstan (3rd -2nd millennium BCE). I am currently submitting this chapter to *Nature: Scientific Reports*. Chapter 3 presents macrobotanical and plant stable isotope research of wheat, barley, peas, and wild taxa from the site of Tasbas in the Dzhungar Mountains of Kazakhstan (3rd millennium BCE - 1st millennium CE). I plan to submit this chapter to *Journal of Archaeological Science* or *Antiquity*. Chapter 3 presents a published paper reporting on plant stable isotopes research of barley from three Western Tibet sites, Piyang, Jiweng, and Dingdong (1st millennium BCE – 1st millennium CE). This paper was published in *Frontiers in Environmental Archaeology* October 31st, 2024, and appears here in a preprint format. Chapter 4 forms the discussion and conclusion of the dissertation where I synthesize the results of the three case studies within the broader framework of agricultural systems and prehistoric food

globalization. Within this chapter, I also compare these results to additional analyses I conducted on the pastoralist site of Koken (3rd-1st millennium BCE) in north-eastern Kazakhstan and additional agropastoral Tibetan sites of Bangga (3rd-1st millennium BCE) and Kaerdong (1st millennium CE) to further develop the concept of localizing cultivation across Eurasia. Appendices for all chapters follow the conclusion.

A note on terminology: I use the term Inner Asia to refer to the broad region that encompasses Central Asia, the Tibetan Plateau, and Mongolia. Central Asia historically has been used to reference the countries of Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan, Tajikistan, and Xinjiang, China. When appropriate (such as when used in the source material or when referencing specifically this region), I use the term Central Asia.

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Chapter 2:

Investment in plant cultivation at the Bronze Age site of Chap, Kyrgyzstan

2.1 Introduction

The mountainous regions of Inner Asia provide interesting case studies for understanding the breadth of landscape utilization through history. Paleolithic hunter gatherers, Bronze and Iron Age agropastoralists and historic Silk Road traders have used the valley corridors and mountain pastures for millennia to create interconnected cultural and economic systems that shaped the history of Eurasia. Of particular interest to this study is the *prehistoric food globalization* process that began prior to 5000 BCE and saw the spread of plant and animal domesticates across the Eurasian continent (Liu et al., 2019). Research in the last 15 years has exponentially expanded our knowledge of the timelines and routes of this globalization process, showing a protracted diffusion of wheat, barley, legumes, broomcorn and foxtail millet, pigs, sheep, goats, cattle, and horses across the landmass (Frachetti et al., 2010; Spengler et al., 2014c; Motuzaite-Matuzeviciute et al., 2017, 2019b, 2015; Jones et al., 2016b; Liu et al., 2017, 2019; Lister et al., 2018; Hermes et al., 2019; Zhou et al., 2020; Gao et al., 2021; Dal Corso et al., 2022; Endo et al., 2023). Robust archaeobotanical and faunal assemblages from several sites across the mountains of Inner Asia connect these two domestication centers and display the integral role highland communities, engaging in some form of mobile pastoralism and agropastoralism, played in not only spreading domesticates, but integrating and modifying the plants themselves to cultivate them in agriculturally risky high elevation landscapes (Spengler et al., 2016, 2013b, 2014c, 2014a; Doumani et al., 2015; Ananyevskaya et al., 2018; Li and Dong, 2018; Taylor et al., 2019;

Zhou et al., 2020; Motuzaite-Matuzeviciute et al., 2020, 2022b; Tian et al., 2022; Hermes et al., 2022; Li et al., 2022). Less is known about the strategies employed by communities in the mountainous regions of Inner Asia to successfully cultivate crops in tandem with their mobile pastoralist activities. Here, I address this question by using plant stable isotopes, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, to assess the water availability and soil nutrition conditions available for free-threshing wheat (*Triticum aestivum/durum/turgidum*) and 6-row naked (*Hordeum vulgare* var. *nudum*) and hulled (*Hordeum vulgare* var. *vulgare*) barley from the Bronze and Iron Age sites of Chap I and II in the Tien Shan Mountains of Kyrgyzstan.

Previous research using stable $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ isotopes inform us about human and animal diets, migration, herding practices across Inner Asia, particularly highlighting the emergence of pastoralism, shifts in foddering, and tracing millet consumption and cultivation across the region (O'Connell et al., 2003; Ling et al., 2013, 2016; Motuzaite-Matuzeviciute et al., 2015, 2016, 2022a; Liu et al., 2016b; Hermes et al., 2018, 2019, 2022; Vaiglova et al., 2021). The use of stable isotopes on archaeological plant material remains limited in Inner Asia, but recent results from the eastern Tianshan and western Tibetan Plateau begin to show diverse cultivation strategies employed by agropastoralists in the 2nd millennium BC to 1st millennium CE. (Tian et al., 2022; Ritchey et al., 2024). In the Eastern Tianshan, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of domesticate cereals from 1300 BCE to 300 CE indicate increasing pastoralism and less investment in plant cultivation (Tian et al., 2022). On the western Tibetan Plateau, however, there is very intensive cultivation of barley grains between 1000 BCE to 100 CE (Ritchey et al., 2024). I add to this growing literature by analyzing the nature of wheat and barley cultivation at one of the earliest agropastoral sites in the IAMC.

Stable isotope analyses of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of archaeological plant remains provide information regarding the plants' growing conditions. $\delta^{13}\text{C}$ values reflect water availability during cultivation, after accounting for changes in atmospheric carbon through time with a calculation from $\delta^{13}\text{C}$ to $\delta^{13}\text{C}_{\text{plant-air}}$ (Farquhar et al., 1989; Araus et al., 1997, 1999a; Wallace et al., 2013). $\delta^{15}\text{N}$ values allow for the assessment of soil ^{15}N enrichment during plant growth (Bogaard et al., 2007; Fraser et al., 2011; Styring et al., 2018). Natural and cultural factors influence these measurable values and experiments provide guidelines for interpreting the role of anthropogenic activities in growing conditions. Together, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values allow for an assessment of ancient strategies of water and soil maintenance and have been used to investigate early agricultural management in the Middle East, Europe, East Asia (Bogaard et al., 2013; Vaiglova et al., 2014a; Styring et al., 2016b; Li et al., 2022) and recently in Inner Asia (Tian et al., 2022; Ritchey et al., 2024). Further, the isotopic signatures and the habitats of recovered wild taxa provide insight into the growing conditions of cereal crops and the overall characteristic of the surrounding anthropogenic environment (Jones et al., 1999; Jones, 2002; José-María et al., 2010; Carmona et al., 2020). I compare stable isotope analyses of domesticated cereal grains with those of arable taxa and examine the broader landscape from an analysis of the wild taxa recovered in the archaeobotanical assemblage.

The cultivation and herding systems at Chap, while conceptually opposed, were effectively integrated within its agropastoral economy. For a mixed agropastoral economy, like the one evidenced at Chap, labor would need to be negotiated between cultivation and other tasks, particularly the management of livestock herds. At least for a portion of the population, mobility in livestock herding would place strains on the labor requirements needed for crop management (Lees & Bates, 1974). Further, crop production depends on soil quality, with

intensification requiring more labor and resources per unit of land to sustain yields and prevent shortages (Boserup, 1965; Morrison, 1994; Halstead, 2006, p. 45). Farmers might also employ extensification by distributing labor over larger areas (Halstead, 1995, 2000). Conversely, pastoral systems rely on extensive labor, focusing on pasture quality and access along with herd size to enhance productivity and manage risks (Boserup, 1965; Khazanov, 1983; Barfield, 1999; Halstead, 2000; Kradin, 2015). Plant stable isotope analysis, complimented by an analysis of wild seed assemblages, provides proxies for investigating these labor investments.

2.2 Environmental and Cultural Context

The Chap sites (42° 10'51.7" N, 75°51'3.64" E) are in Kochkor Valley of the central Tien Shan Mountains, Kyrgyzstan at 2000 meters above sea level (masl hereafter). The sites are near a natural snowmelt-fed spring on a south-facing slope of foothills in the southeast of the valley. Today, the valley has a unique microclimate that is favorable to year-round agropastoralism with mild annual temperatures and exposed bedrock that stores solar energy that prevents winter snow accumulation (Chupakhin, 1959). However, the steep surrounding mountains receive more intense weather, with south-facing slopes often experiencing snowstorms in the summer preventing successful cereal cultivation above 2600 masl. Farming is currently concentrated in the valley floor utilizing terraced and stream irrigated systems (Motuzaite-Matuzeviciute et al., 2019b, 2020, 2021b, 2022b). Modern precipitation averages 200 mm/year with maximum rainfall during July and 80% of rainfall occurring between May and September (Chupakhin, 1959; Böckel and Becker, 2014). There are, however, elevated evaporation rates which maintain a relatively dry local climate. As such, vegetation is sparse and dominated by arid steppe grasses and shrubs such as *artemisia* spp. and *stipa* spp, with larger vegetation concentrated along

seasonal waterways and drainages (Kasymov, 2015; Rouse et al., 2022). This dryer climate requires water management for successful cultivation, evidenced through ancient irrigation features spread all over the area and modern-day irrigation ditches (*aryks*) and canals in the valley floor (Rouse et al., 2022)

The Kochkor valley has a deep archaeological history, likely due in part to the valley's relatively hospitable climate, even at 1800-2000 masl. Evidence of Middle-and Upper Paleolithic, Bronze and Iron Ages, and historic Silk Road Karakhanid sites are present in the region (Amanbayeva et al., 2011; Abdykanova, 2014; Ivanov, 2017; Motuzaite-Matuzeviciute et al., 2021b, 2022b). Petroglyph, ceramic, and subsistence evidence show connections to broader Inner Asia during the Bronze and Iron Ages and Silk Road periods (Kuz'mina, 1986; Ivanov, 2017; Motuzaite-Matuzeviciute et al., 2022b). Chap I and II are two distinct occupation events that have evidence of multiple domestic layers including fireplaces, ovens, burial pits, domestic pits and floors, and structural features. Bayesian statistics models date the Chap I farmstead occupation from 1102-926 cal BCE to 916-816 cal BCE. Chap II, (situated under Chap I and separated by approximately 1 meter of sterile silty sediment) is dated to 2474 – 2162 cal BCE (Motuzaite-Matuzeviciute et al., 2022b; Spate et al. forthcoming 2025). The abundance of domesticate cereal crops, crop processing byproducts, pastoral faunal remains, and certain ceramic styles indicate an agropastoral occupation, where at least some of the community remained sedentary to manage possibly spring- and autumn- sown crops, beginning in the 3rd millennium BCE and continuing in the 2nd to 1st millennium BCE (Motuzaite-Matuzeviciute et al., 2020, 2021b, 2022b). Zooarchaeological and ZooMS analyses of Chap I and Chap II sites point to a high reliance on sheep/goats than cattle. Further, a high survival of older animals and a preference towards sheep over goats suggests a selection for secondary products, such as milk

and wool (Ananyevskaya et al., 2021). Unmanned Aerial Vehicles (UAV) photogrammetry, geophysical surveys, and subsequent analyses in the surrounding area show a long-term, heavily managed landscape including irrigation ditches, altered natural waterways, check dams and diversion walls, catchment areas, and terraces (Rouse et al., 2022).

The sites can be considered within the Inner Asian Mountain Corridor (IAMC) (coined by Frachetti (2012), where Bronze Age communities are theorized to be connected through institutional networks that allowed for the movement of beliefs, technologies, people, cultures and their plant and animal domesticates across the highland valleys and ridges of the Tian Shan, Dzhungar, Altai, Hindu Kush, Kopet Dag, Pamir, and western Himalayan Mountains. Agropastoral activities tie these communities together but manifest in unique ways regionally and at each site. Significantly, between the 3rd-1st millennium BCE, these communities used the mountains as conduits for spreading Southwest Asian domesticates, like wheat (*Triticum* spp.), barley (*Hordeum vulgare*), peas (*Pisum sativum*), sheep (*Ovis aries*), goats (*Capra hircus*), horse (*Equus caballus*), and cattle (*Bos taurus*), north and eastward into ancient China and East Asian domesticates, like broomcorn (*Panicum miliaceum*) and foxtail (*Setaria italica*) millet, westward into Inner Asia and potentially beyond to Europe (Frachetti et al., 2010; Spengler et al., 2014c; Motuzaite-Matuzeviciute et al., 2015, 2017, 2019b; Liu et al., 2019; Zhou et al., 2020). Their unique adoptions of livestock herding and plant cultivation, coupled with an interconnected material culture tradition in the mountainous regions of Inner Asia, provide a case study for understanding local manifestations of labor organization, identity, and social structure. A key, under researched component is the particular agricultural strategies employed at each site in the IAMC. Did agropastoralists adopt novel crops together with their associated management systems or did they modify them to better fit an agropastoral lifestyle in the mountainous

Kyrgyzstan Tien Shan? In this study, I address this question through analyzing proxies for labor investment in cereal crops through plant stable isotope analyses of cultivated wheat and barley grains and associated wild seeds from Chap I and II.

2.3 Materials and Methods

I used R (version 3.4.1) packages ggplot, EnvStats, and esci to create graphs and perform statistical analyses. I used Jamovi (Versions 2.4.11) to calculate confidence interval statistics and plots.

2.3.1 Macrobotanical materials and analysis

During both occupation periods at Chap, abundant macrobotanical remains were recovered and subsequently analyzed. Previous publications present comprehensive discussions of these results (Motuzaite-Matuzeviciute et al., 2019b, 2020, 2021b, 2022b) and I present a brief summary here to contextualize the materials analyzed in this study (Table 1).

Table 1. Summary of seed counts grouped by site, Chap I and II, including total recovered and sub-sampled for this study. Additional wild taxa were recovered from both sites, but only those sub-sampled for isotopic analysis are summarized here. Original data from Chap I reported in Motuzaite Matuzeviciute et al. (2021b) and Chap II reported in Motuzaite Matuzeviciute et al. (2022b).

	Total identified	Analyzed in this study	
	Count	Total Seeds	Total Samples
Chap I			
Domesticated			
Naked Barley	1325	53	53
Hulled Barley	338	15	15
Barley	231 whole, 3650 frag.		
Free-threshing wheat	82	25	25
Foxtail Millet	19		
Broomcorn Millet	19		
Pea	20		
Wild			
<i>Chenopodium</i> spp.	1710	149	6
<i>Carex</i> spp.	1758	113	8
<i>Medicago/Trifolium/Trigonella</i>	8151	181	13
<i>Galium</i> sp.	1558	157	15
Poaceae spp.	426	35	5
<i>Bromus</i> sp.	412	6	1
<i>Poa</i> sp.	39	14	2
Chap II			
Domesticated			
Naked Barley	908	61	61
Hulled Barley	17	3	3
Barley	70 whole, 249 frag.		
Free-threshing wheat	929 whole, 427 frag.	58	58
Wild			
<i>Chenopodium</i> spp.	1710	234	9
<i>Carex</i> spp.	792	119	7
<i>Medicago/Trifolium/Trigonella</i>	74	27	4
<i>Galium</i> sp.	105	31	5
Poaceae sp.	57	4	1
<i>Poa</i> sp.	7	3	1

1,210 liters of sediment were floated at Chap I from 43 contexts, representing four main activity zones at the site. Barley is the most abundant cereal: naked (*Hordeum vulgare* var.

nudum) (n = 1,325), hulled (*Hordeum vulgare* var. *vulgare*) (n = 338) grains, undetermined *Hordeum* sp. (n = 231), and rachis internodes (n = 704), followed by 71 free-threshing wheat, of a compact morphotype (*Triticum aestivum/durum*), 2 *Triticum* rachis internodes, 11 undetermined *Triticum* sp., foxtail millet (*Setaria italica*) (n = 19), and broomcorn millet (*Panicum miliaceum*) (n = 19). Additionally, 20 peas (*Pisum sativum*) are present. Wild taxa include abundant *Chenopodium* spp., *Medicago/Trifolium/Melilotus* spp., *Trigonella* sp., *Galium* spp., *Silene* cf. *venosa*, *Vaccaria* cf. *hispanica*, various wild grasses (including *Bromus* sp., *Agrostis* sp., *Festuca* sp.), and sedges (*Carex* spp.) (Motuzaite-Matuzeviciute et al., 2021b). For this plant stable isotope study, I analyzed 15 hulled barley, 53 naked barley, 25 free-threshing wheat, 149 (6 samples) *Chenopodium* spp., 181 (13 samples) *Medicago/Trifolium/Triogenlla* spp., 157 (15 samples) *Galium* spp., 113 (8 samples) *Carex* spp. and 55 (8 samples) wild Poaceae.

From Chap II, 306 liters of sediment from 13 contexts were floated. Like Chap I, barley dominates the assemblage: naked (n = 908), hulled (n = 17), and undetermined *Hordeum* sp. (n = 70). Multiple species of free-threshing wheat are also plentiful (*Triticum aestivum/durum/turgidum*) (n = 922 whole) and cf. *Triticum dicoccum/carthlicum* (n=21 whole). Remnants of cereal processing are present, with abundant barley chaff, including naked and hulled rachis, rachis internodes, and glumes (n= 38) and some wheat rachis internodes (n = 36) (Motuzaite-Matuzeviciute et al., 2022b). No millets or legumes were recovered from Chap II. Weed taxa are similar in composition to Chap I, dominated by goosefoot (*Chenopodium* spp.) and sedges (*Carex* spp.). Also present are *Silene noctiflora*, *Vaccaria* sp., *Melilotus/Medicago/Trifolium* spp., *Galium* spp., and wild grasses (including cf. *Eragrostis* sp., *Agrostis* sp., and *Bromus* sp.) (Motuzaite-Matuzeviciute et al., 2022b). For this plant stable

isotope study, I analyzed 3 hulled barley, 61 naked barley, 58 free-threshing wheat, 234 (9 samples) *Chenopodium* spp., 27 (4 samples) *Medicago/Trifolium/Triogenlla* spp., 31 (5 samples) *Galium* spp., 119 (7 samples) *Carex* spp. and 7 (2 samples) wild Poaceae. I was limited in sampling more hulled barley due to the overall small sample size and ethically conserving material; 17 total hulled barley were recovered at Chap II compared to the 338 identified at Chap I.

In total, I analyzed 18 hulled barley, 114 naked barley, 122 free-threshing wheat, 383 (15 samples) *Chenopodium* spp., 208 (17 samples) *Medicago/Trifolium/Triogenlla* spp., 188 (20 samples) *Galium* spp., 232 (15 samples) *Carex* spp. and 62 (10 samples) wild Poaceae.

2.3.2 Plant stable isotope analysis

I selected grains that looked well-preserved from their surface texture and wholeness. For cereal grains, I followed Vaiglova et al. (Vaiglova et al., 2022) and Stroud et al. (2023a)'s guidelines for assessing grains from optimal charring conditions to ensure recovery of isotopic values. Through visual analysis of seed coat preservation, morphology, and internal matrix composition, I classified wheat and barley grains into “good”, “borderline”, and “poor” categories (Supplementary Figure 1). In their experiments, Stroud et al. (2023a) find that there is variation of isotope values across charring conditions. Thus, I compared our classifications against associated $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values to assess any potential effect of grain condition on isotopic composition. Visual inspection of the results indicates no substantial patterns in isotopic value between charring status classifications (Figure 2). To further interrogate, I estimated the 95 % confidence intervals (CIs, reported as [lower level, upper level]) of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ means of each charring status category (Supplementary Table 2, Supplementary Figure 2). The group

means for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are nearly identical across charring status categories. For $\delta^{13}\text{C}$, the calculate group means are good 17.5 ‰ [5.6, 6.6], n = 62, borderline 17.4 ‰ [17.1, 17.7], n = 51, and poor 17.5 ‰ [17.30, 17.76], n = 102. For $\delta^{15}\text{N}$, the good and borderline group means are nearly identical, good 6.1 ‰ [5.6, 6.6] and borderline 6.1 ‰ [5.5, 6.6]. The poor category for $\delta^{15}\text{N}$ is slightly lower than good and borderline, with a mean of 5.7 ‰ [5.3, 6.1]. The mean difference in between the poor category and the combined values of good and borderline is -0.4 ‰ [-0.9, 0.2]. This suggests that the mean difference between the $\delta^{15}\text{N}$ values of the poor and the combined good/borderline groups is plausibly anywhere between -0.9 and 0.2 (Supplementary Figure 2 C). Given the tightness of this CI and the notable overlap in the CIs of poor and the combined good/borderline groups, I interpret this as a non-substantial difference. From these calculations, I do not see an impact of charring status on isotope value in our dataset and use all grains, regardless of charring status, in subsequent analyses.

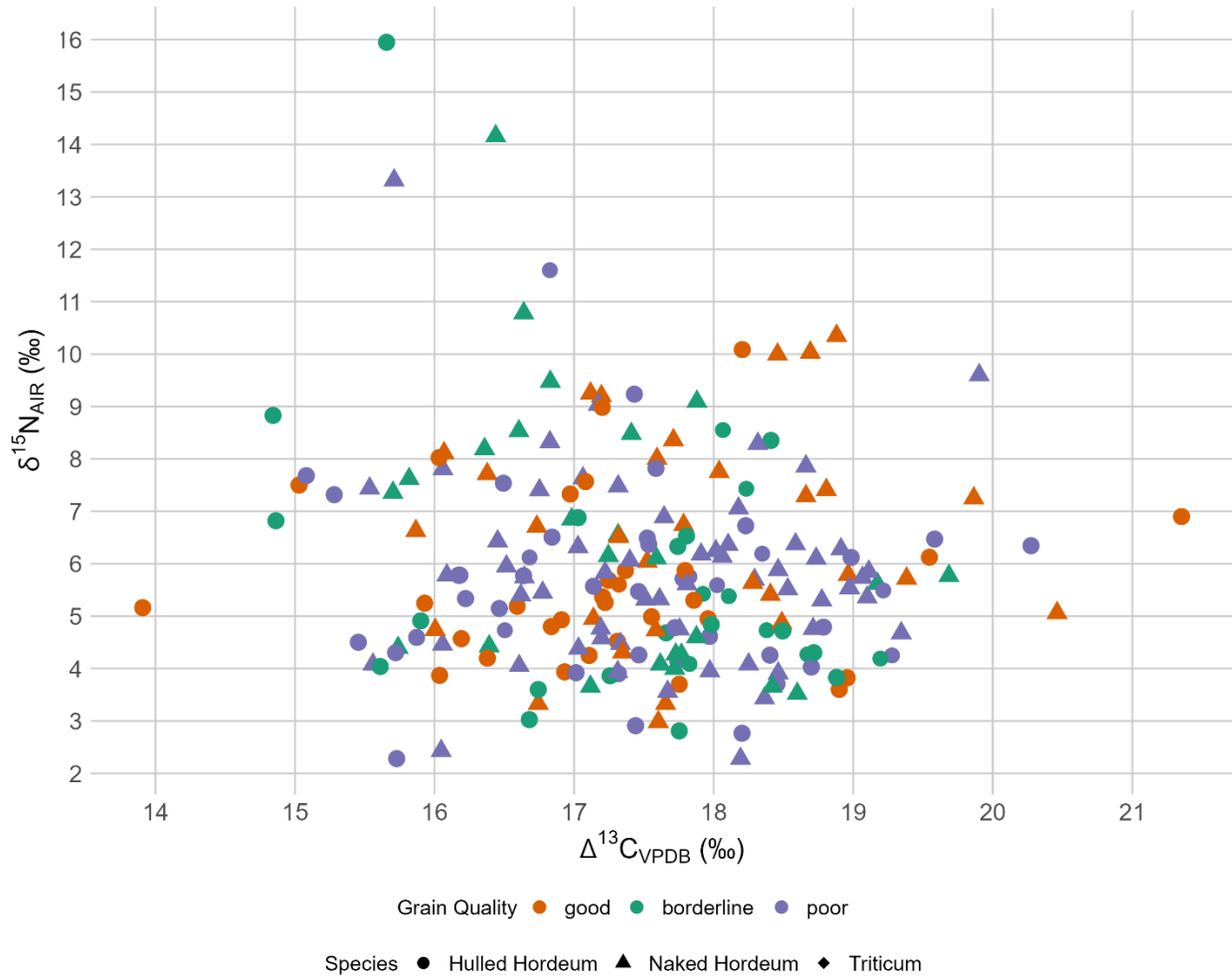


Figure 2. Scatterplot with the $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of hulled barley, naked barley, and wheat grains grouped by assigned grain quality: borderline, good, and poor.

I ran single-grain analyses for all wheat and barley. I combined multiple seeds (ranging from 3-36 depending on seed weight) for the smaller wild taxa into single samples to ensure adequate mass. For the majority, these combined wild samples collected seeds from the same context. For a few, I combined wild taxa seeds from multiple associated contexts to ensure adequate mass (Supplementary Table 3).

After assessing grain preservation status, I prepared grains and wild seed samples for isotopic analyses following Vaiglova et al. (2014b)'s pretreatment protocol. I cleaned each seed

of any visible surface contaminants and crushed them into a fine powder. I then used a gentle acid wash to remove an exogenous soil carbonate from the sample by soaking each sample with 0.5 M hydrochloric acid heated at 80 °C for 30 minutes. After three washes with deionized water, I dried each sample in a vacuum freezer for eight hours. I weighed out 900 µg of the dried samples and placed them into tin capsules. I conducted the carbon and nitrogen stable isotope analyses using an Elemental Analyzer coupled to a Thermo Delta V Plus Continuous Flow Isotope Ratio Mass Spectrometer (EA–IRMS) housed at the Department of Earth, Environmental, and Planetary Sciences at Washington University in St. Louis, USA. I calibrated the raw $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values relative to VPDB and AIR, respectively, with the standards of USGS 40 ($\delta^{13}\text{C} = -26.4 \text{ ‰}$, $\delta^{15}\text{N} = -4.5 \text{ ‰}$), USGS41a ($\delta^{13}\text{C} = +36.6 \text{ ‰}$, $\delta^{15}\text{N} = -4.5 \text{ ‰}$), and urea ($\delta^{13}\text{C} = -45.4 \text{ ‰}$, $\delta^{15}\text{N} = -0.9 \text{ ‰}$). I used two in-house standards for linearity and check standards: acetanilide ($\delta^{13}\text{C} = -29.5 \text{ ‰}$, $\delta^{15}\text{N} = +47.6 \text{ ‰}$) and BR millet (Bob’s Red Mill millet flour; $\delta^{13}\text{C} = -13.2 \text{ ‰}$, $\delta^{15}\text{N} = +3.3 \text{ ‰}$). 16 replicates were conducted to aid in assessing precision and accuracy. Averaged values of these replicates are used in the results and analyses. Precision ($u(Rw)$) was determined to be $\pm 0.36 \text{ ‰}$ for $\delta^{13}\text{C}$ and $\pm 0.24 \text{ ‰}$ for $\delta^{15}\text{N}$. Accuracy or systematic error ($u(bias)$) was determined to be $\pm 0.25 \text{ ‰}$ for $\delta^{13}\text{C}$ and $\pm 0.29 \text{ ‰}$ for $\delta^{15}\text{N}$ based on calibration standard and check standard measurements. Using the equations from Szpak et al. (2017), the total analytical uncertainty was determined to be $\pm 0.44 \text{ ‰}$ for $\delta^{13}\text{C}$ and $\pm 0.38 \text{ ‰}$ for $\delta^{15}\text{N}$.

To interpret $\Delta^{13}\text{C}$ values of archaeological grains, I use Li et al. (2022) watering thresholds developed based on the experimental thresholds provided by Wallace et al. (2013), where $\Delta^{13}\text{C}$ values below the Optimal Watering Threshold (OWT) suggest water availability limited plant growth, values above the OWT suggest water availability that did not limit plant

growth, and values above the Superfluous Watering Threshold (SWT) suggest water availability well above the plant's need. Due to taxonomic differences in carbon fractionation, barley has an OWT of 17 ‰ and a SWT of 18.5 ‰ and wheat a OWT of 16 ‰ and SWT of 17 ‰. See section 1.3 Plant Stable Isotope Principles for an in-depth discussion.

To account for natural sources of N, we can calculate a natural threshold for $\delta^{15}\text{N}$ through measuring the $\delta^{15}\text{N}$ values of archaeological remains of wild herbivores which subsisted largely on natural vegetation (Styring et al., 2024). There is a known N trophic level offset of approximately 3-5 ‰ between diet and consumer tissues, such that herbivore tissues are 3-5 ‰ higher than the values of their vegetative diet. (DeNiro and Epstein, 1981; Minagawa and Wada, 1984). I assume wild herbivores did not consume plants from anthropogenically modified landscapes, but they could have raided tended fields. With these assumptions considered, I can create a natural baselevel for $\delta^{15}\text{N}$ values to compare the results of the archaeological plant remains. Archaeological plant $\delta^{15}\text{N}$ values measuring substantially above this natural baselevel can then be considered as anthropogenically sourced. Available data for archaeological animal $\delta^{15}\text{N}$ isotopes for the Kyrgyzstan are presented in Motuzaite Matuzeviciute (2022a). However, only one wild archaeological herbivore – a specimen identified as a wild goat – was analyzed from the site of Aigyrzhal in the Naryn Valley with a $\delta^{15}\text{N}$ value of 4.9 ‰. To calculate a more robust nitrogen baselevel, I also included the results of all herbivores analyzed from sites in the Kochkor Valley, including Chap I and II, Kara-Tumshuk, Kok-Sai, and Kok-Tash (Supplementary Table 1). These values range from 11.92 ‰ – 4.19 ‰. The higher values suggest that at least some of all of the diets of some of these herbivores were supplemented with nitrogen enriched cereal crops. With all Kochkor herbivores plus the wild goat from Aigyrzhal, the average $\delta^{15}\text{N}$ value is 7.6 ‰ (n = 53). Offset by the approximate 3-5‰ trophic difference, the

range for a natural baselevel is 2.6 – 4.6 ‰. If I remove the samples with higher $\delta^{15}\text{N}$ values – with an arbitrary cutoff of 7‰ – and sample those only below, I calculate an average $\delta^{15}\text{N}$ value of 6.3 ‰ (n = 19). Offset by the approximate 3 – 5 ‰ trophic difference, the range for a natural baselevel is 1.3 -3.3 ‰. I believe this calculation to be a more accurate representation of natural vegetation baselevel and use this range to compare the results of our $\delta^{15}\text{N}$ analyses.

2.3.3 Wild Taxa Analysis

To contextualize the results of the plant stable isotope analysis and gain a more robust understanding of the anthropogenic and natural environment at Chap I and II, I compared the cereal grain isotope data with isotope results of a subsection of recovered wild taxa. I chose the wild taxa for isotopic analyses based on abundance in assemblage and potential relation to cereal crops – these genera often grow in the plots of cereal grains today in the region. These wild taxa were grouped together based on identified genera or families when necessary. The groups include: *Chenopodium*, *Galium*, *Carex*, wild Fabaceae, and wild Poaceae. The wild Fabaceae group includes seeds identified as *Medicago*, *Trifolium*, and *Trigonella*. These are often hard to distinguish morphologically and grow in similar habitats. For ease of comparison, they were combined. Similarly, the wild Poaceae group includes seeds identified as Poaceae, *Poa*, and *Bromus*.

Additionally, I compared the habitats of all recovered wild taxa to the cereal grain isotope results. For analyses, the wild taxa were assigned three broad habitats based on their preferred growing conditions: ruderal (nitrogen-rich, disturbed landscapes), wetlands (moist meadows, moisture-rich), and grassland (semi-arid/arid, grassland/steppe) (Supplementary Table 7). Of the wild taxa from each site, I calculated the proportions of taxa representing each habitat group.

2.4 Results

Summarized results of the $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analyses for cereal grains are reported in and displayed Table 2 and as boxplots in Figure 3; a complete report of the results is in (Supplementary Table 3).

Table 2. Calculated measurements of wheat, hulled barley, and naked barley at Chap I and II: $\Delta^{13}\text{C}$, $\delta^{15}\text{N}$, Length, Breadth, Thickness, and Length/Breadth ratio. Measurements include mean, standard deviation (SD), 95 % CI [Lower level, Upper level], and median.

	Chap II 2474 – 2162 cal BCE			Chap I 1065 -825 cal BCE			Time Periods combined		
	Wheat n = 58	Hulled Barley n = 3	Naked Barley n = 61	Wheat n = 25	Hulled Barley n = 15	Naked Barley n = 53	Wheat n = 83	Hulled Barley n = 18	Naked Barley n = 114
$\Delta^{13}\text{C}$ mean $\pm$ SD (1 σ) (‰)	17.1 $\pm$ 1.1	18.1 $\pm$ 1.0	17.5 $\pm$ 0.8	17.6 $\pm$ 1.64	18.0 $\pm$ 0.8	17.7 $\pm$ 1.3	17.2 $\pm$ 1.3	18.0 $\pm$ 0.8	17.6 $\pm$ 1.1
95 % CI [LL, UL]	[16.8, 17.1]	[15.7, 20.5]	[17.3, 17.7]	[16.9, 18.2]	[17.5, 18.4]	[17.4, 18.1]	[17.0, 17.5]	[17.6, 18.4]	[17.4, 17.6]
median	17.2	17.8	17.4	17.7	18.1	17.8	17.3	18	17.6
$\delta^{15}\text{N}$ mean $\pm$ SD (1 σ) (‰)	5.3 $\pm$ 1.5	4.6 $\pm$ 0.8	5.6 $\pm$ 1.7	6.0 $\pm$ 2.8	6.1 $\pm$ 1.9	6.9 $\pm$ 2.3	5.53 $\pm$ 1.98	5.8 $\pm$ 1.8	6.2 $\pm$ 2.1
95 % C [LL, UL]	[5.0, 5.7]	[2.5, 6.7]	[5.2, 6.0]	[4.8, 7.1]	[5.0, 7.1]	[6.2, 7.5]	[5.10, 5.96]	[4.9, 6.8]	[5.8, 6.6]
median	5.2	4.2	5.5	5.2	5.6	6.4	5.16	5.5	5.8

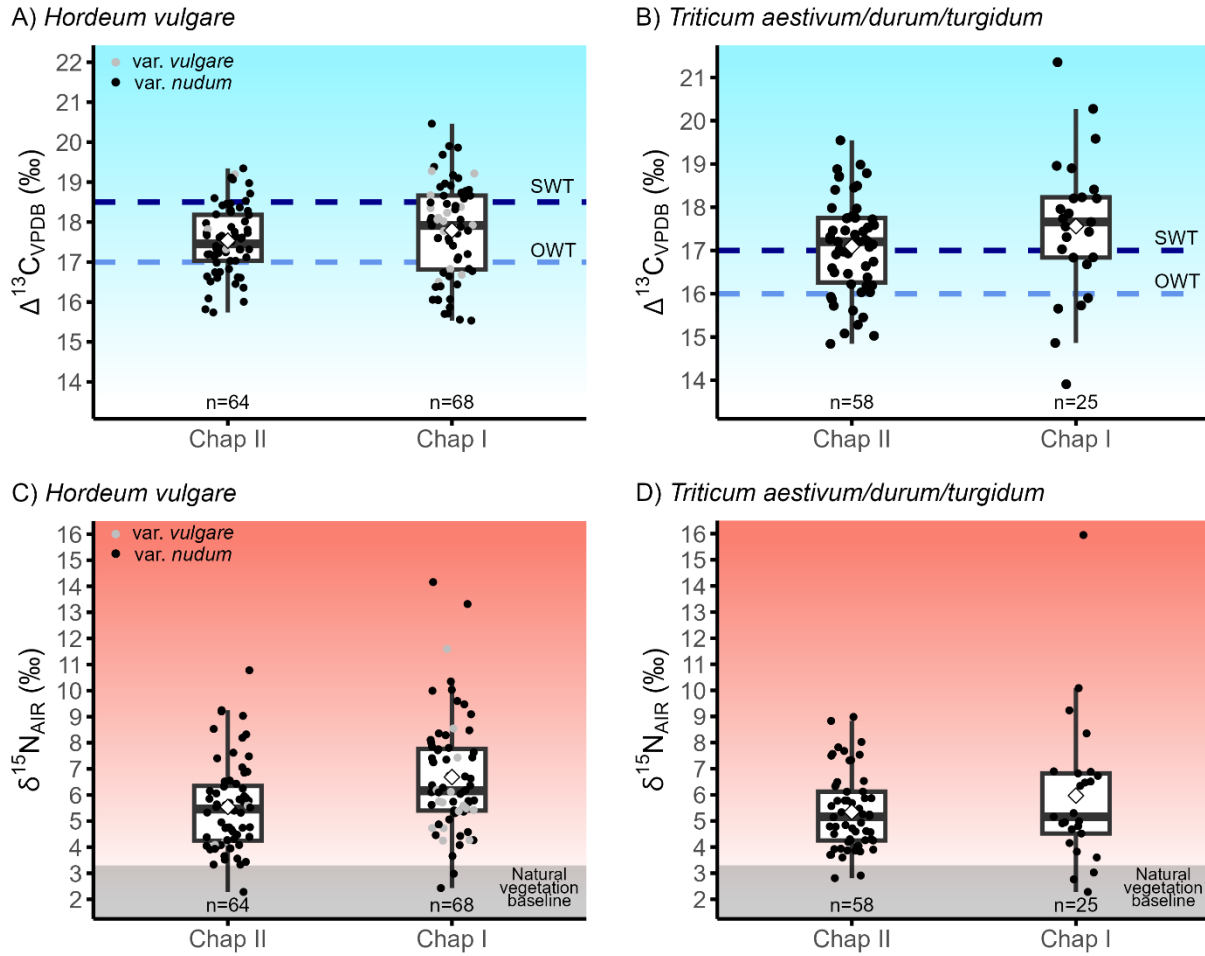


Figure 3. Boxplots presenting $\Delta^{13}C$, A) and B), and $\delta^{15}N$, C) and D), values of A) and C) *Hordeum vulgare* var. *vulgare* and var. *nudum*, and B) and D) *Triticum aestivum/durum/turgidum* from Chap I and II. Diamonds represent means. Blue horizontal lines in A) and B) represent the Optimal Watering Threshold (OWT) and Superfluous Watering Threshold (SWT) for each barley and wheat and gray areas in C) and D) represent the natural vegetation baselevel of 1.3 - 3.3 ‰.

2.4.1 Carbon

The results of the $\Delta^{13}C$ analyses of cereal grains show that wheat grains fall primarily above the OWT and SWT thresholds. Conversely, many more barley grains fall below the OWT. For barley, I analyzed both naked and hulled grains. Hulled barley grains have slightly higher mean $\Delta^{13}C$ values: hulled 18.0 ‰ [17.6, 18.4], n = 18, and naked 17.6 ‰ [17.4, 17.8], n = 114, with a

mean difference of -0.4 ‰ [-0.9, 0.1] (Supplementary Table 4, Supplementary Figure 3). This suggests that the mean difference between the $\delta^{13}\text{C}$ values of naked and hulled barley is plausibly anywhere between -0.9 and 0.1. There is some overlap in the CIs, suggesting this is not a notable difference in means. Since there are no notable differences between the barley types, I combined hulled and naked barley for the following analyses. The mean $\delta^{13}\text{C}$ value of wheat grains is 17.2 ‰ [17.0, 17.5], $n = 83$.

For both barley and wheat, I see an increase in the mean $\delta^{13}\text{C}$ values through time (from Chap II to Chap I). For barley (Figure 3 A), most grains from Chap II are concentrated below the SWT threshold, with many below the OWT. From Chap I, I see more grains above the SWT threshold, with a wider overall spread of $\delta^{13}\text{C}$ values. With naked and hulled barley grains combined, from Chap II 17.5 ‰ [17.3, 17.8] to Chap I 17.8 ‰ [17.5, 18.0], there is an increase of mean $\delta^{13}\text{C}$ values by 0.3 ‰ [0.5, 1.8] (Supplementary Figure 4 A). This suggests that the mean difference between the $\delta^{13}\text{C}$ values of Chap II and Chap I is plausibly anywhere between 0.5 and 1.8. There is a minor overlap in the CIs between the two time periods. Taken together, the increase in $\delta^{13}\text{C}$ values through time for barley is likely not notable. However, there is a substantial change in the proportion of grains above the SWT through time (Figure 4). Chap II has 12.5 % of grains above the SWT, while Chap I has 29.4%. Further, Chap II has 76.6% of grains above the OWT, while Chap I has 82.1%. These differences in grain proportions through time implies an overall shift in the distribution of grains to higher $\delta^{13}\text{C}$ values.

There is a similar increase in the mean $\delta^{13}\text{C}$ of wheat through time (Figure 3). The mean $\delta^{13}\text{C}$ value of Chap II is 17.1 ‰ [16.8, 17.4], $n = 58$, while for Chap I it is 17.6 ‰ [17.1, 18.1], $n = 25$. There is a mean increase of 0.5 ‰ [-0.1, 1.1] between Chap II and I (Supplementary Figure 4 C). This suggests that the $\delta^{13}\text{C}$ values of Chap II and Chap I are plausibly anywhere

between -0.1 and 1.1. There is a minor overlap in the CIs between the two time periods, suggesting that this is not a substantial difference in means, but is still noteworthy. However, similar to the trends in barley, the proportion of grains above the SWT between the time periods changes (Figure 4). From Chap II, 68% of wheat grains fall above the SWT, while at Chap I 58.6% do.

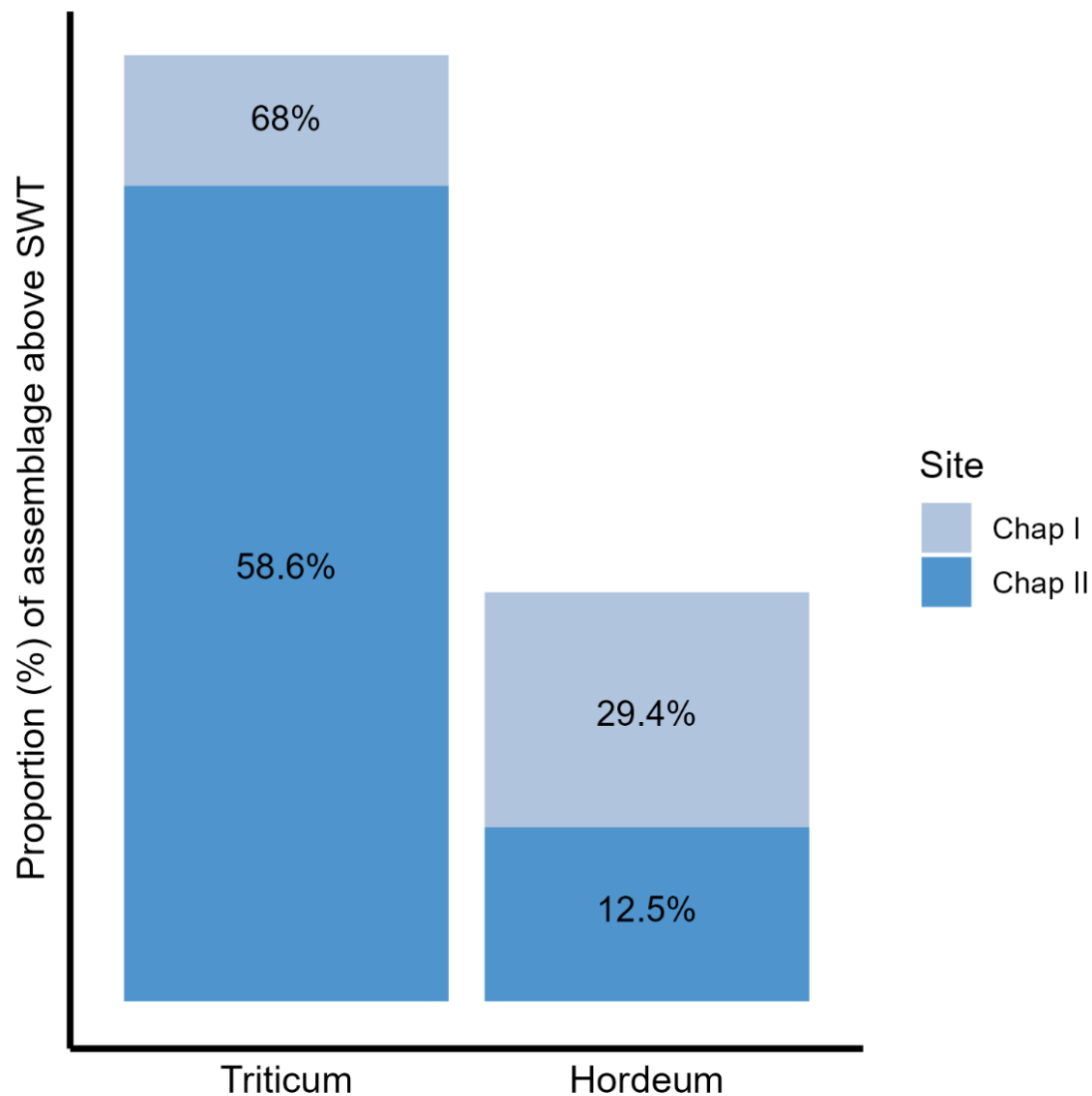


Figure 4. Stacked bar charts presenting the proportion (%) of $\delta^{13}\text{C}$ values of wheat and barley above their respective Superfluous Watering Thresholds (SWT) for Chap I and II.

2.4.2 Nitrogen

The results of the $\delta^{15}\text{N}$ analyses show that most all grains for both wheat and barley are above the calculated maximum natural baselevel of 3.3 ‰ (Table 2, Figure 3). There are slightly more barley grains ($n = 8$) below this baselevel than wheat ($n = 5$). For barley, I analyzed both naked and hulled grains. Naked barley has a higher mean $\delta^{15}\text{N}$ value, 6.2 ‰ [5.4, 6.6] than hulled 5.8 ‰ [4.9, 6.8], with a mean difference of 0.3 [-0.7, 1.4] (Supplementary Table 4, Supplementary Figure 3). This suggests that the mean difference between the $\delta^{15}\text{N}$ values of naked and hulled barley is plausibly anywhere between -0.7 and 1.4. There is considerable overlap between the CIs, suggesting this is not a notable difference in means. Since there are no notable differences between the barley types, I combined hulled and naked barley for the following analyses. The mean $\delta^{15}\text{N}$ value of wheat grains is 5.5 ‰, [5.1, 6.0], $n = 83$. Overall, barley, 6.1 ‰ [5.8, 6.5], $n = 132$, has a greater mean $\delta^{15}\text{N}$ value than wheat, 5.5 ‰ [5.1, 6.0], $n = 83$, with a mean difference of 0.6 ‰ [0.0, 1.2] (Supplementary Table 6, Supplementary Figure 5). This suggests that the mean difference between the $\delta^{15}\text{N}$ values of barley and wheat is plausibly anywhere between 0.0 and 1.2. There is a minor overlap in the CIs, suggesting that this is not a substantial difference in means, but is still noteworthy.

When considering the diachronic trends, there is a notable increase in $\delta^{15}\text{N}$ values for barley (naked and hulled combined) from Chap II, 5.5 ‰ [5.1, 6.0], $n = 64$, to Chap I, 6.7 ‰ [6.2, 7.2], $n = 68$, with a mean increase of 1.1 ‰ [0.5, 1.8] (Supplementary Table 5, Supplementary Figure 4 B). This suggests that the mean difference between the $\delta^{15}\text{N}$ values barley from Chap II and Chap I is plausibly anywhere between 0.5 and 1.8. There is no overlap in the CIs, suggesting this is a notable difference in means. For wheat, there is a slight increase in mean $\delta^{15}\text{N}$ values through time, from Chap II, 17.1 ‰ [16.8, 17.4], $n = 58$, to Chap I, 17.6 ‰

[17.1, 18.1], $n = 25$, with a mean increase of 0.5 ‰ [-0.1, 1.1] (Supplementary Figure 4 D). This suggests that the mean difference between the $\delta^{15}\text{N}$ values of wheat from Chap II and Chap I is plausibly anywhere between -0.1 and 1.1. There is considerable overlap in the CIs, suggesting this is not a notable difference in means.

2.4.3 Wild taxa

The $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wild taxa from Chap I and II are presented in Supplementary Table 3 and Figure 5 as boxplots; results represent homogenized samples of multiple seeds. Due to the small sample sizes of the wild taxa, I limit the statistical analyses to descriptive calculations of mean values. There is an increase in mean $\Delta^{13}\text{C}$ values through time from Chap II to Chap I of *Chenopodium* and wild Poaceae, while *Carex*, *Galium*, and wild Fabaceae decrease through time. There is increase in mean $\delta^{15}\text{N}$ values through time of *Chenopodium*, *Galium*, and wild Fabaceae, while *Carex* and wild Poaceae decrease.

I also plotted the mean and standard deviations of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wild taxa with those of the domesticated cereal grains from Chap I and II (Figure 6). $\Delta^{13}\text{C}$ values are plotted on the x axis. As a C_3 grass, the wild Poaceae sampled have a similar $\Delta^{13}\text{C}$ fractionation process to domesticated cereals and may offer the most interpretive value. At Chap II, wild Poaceae have notably lower $\Delta^{13}\text{C}$ values, > 1 ‰, than domesticated cereals, while for Chap I they are only slightly lower, < 1 ‰. *Galium* has the highest $\Delta^{13}\text{C}$ values for both Chap I and II. *Chenopodium* closely aligned with the $\Delta^{13}\text{C}$ values of domesticated cereals at Chap II, are slightly higher, < 1 ‰ than domesticated cereals at Chap I. *Carex* and *Galium* mean $\Delta^{13}\text{C}$ values are both higher than domesticated cereals, while wild Fabaceae are lower. $\delta^{15}\text{N}$ values are plotted on the y axis. Wild Fabaceae have much lower $\delta^{15}\text{N}$ values than the rest of the taxa for both Chap I and II. At Chap

II, wild Poaceae have the highest $\delta^{15}\text{N}$ mean values, followed by *Chenopodium*, while at Chap I, *Chenopodium* have the highest, followed by *Galium*. At Chap II, *Galium* and *Carex* have higher, but similar $\delta^{15}\text{N}$ values to the domesticated cereals. At Chap I, wild Poaceae mean values are closest to the domesticated cereals, with *Galium* 1-2 ‰ higher and *Carex* 1-2 ‰ lower.

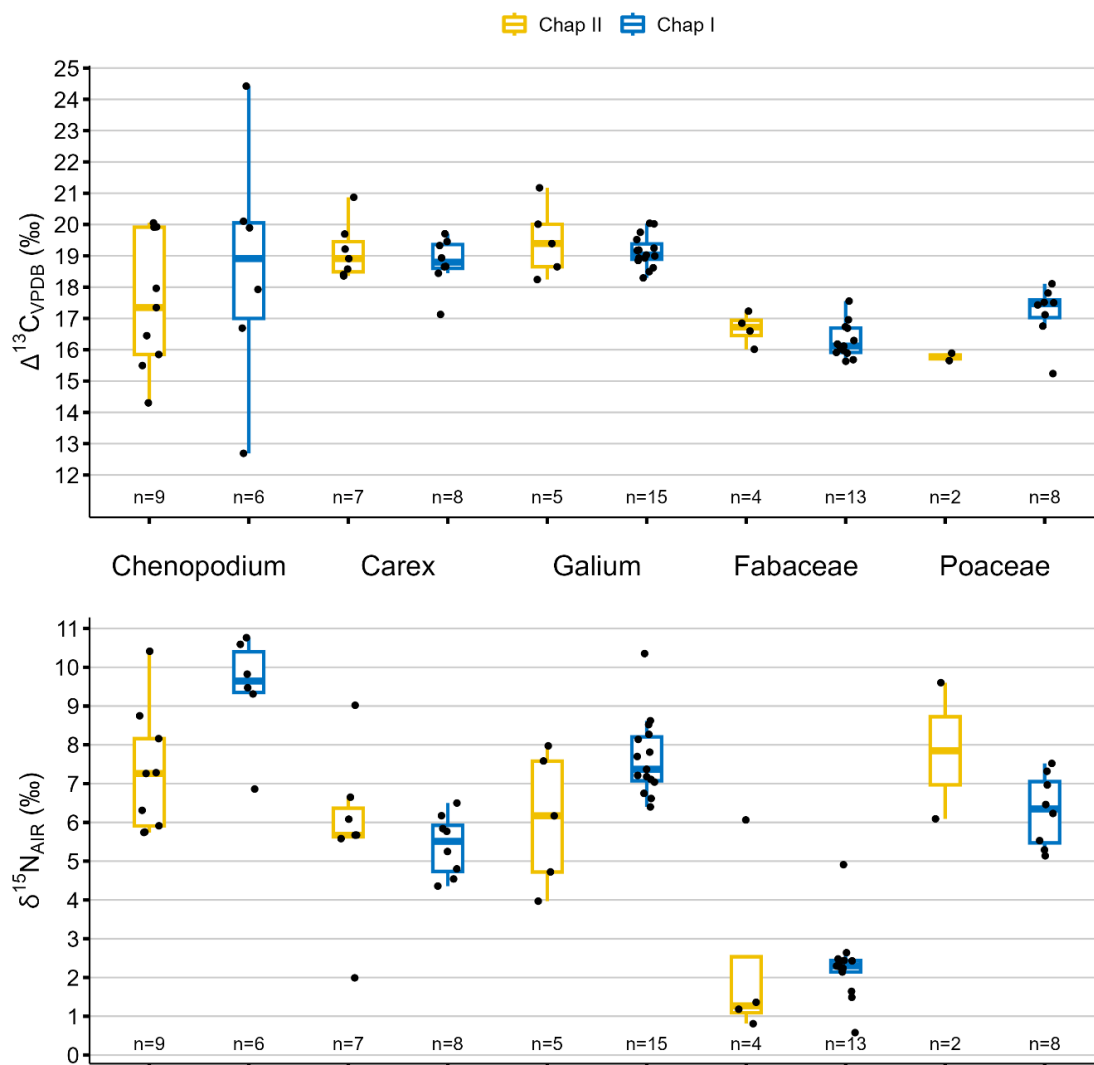


Figure 5. Boxplots of $\Delta^{13}\text{C}$, top, and $\delta^{15}\text{N}$, bottom, of a selection of wild taxa from Chap I, blue, and Chap II, yellow. N represents the number of homogenized samples analyzed, not total number of seeds (which varies between taxa and sample, see Supplementary Table 3).

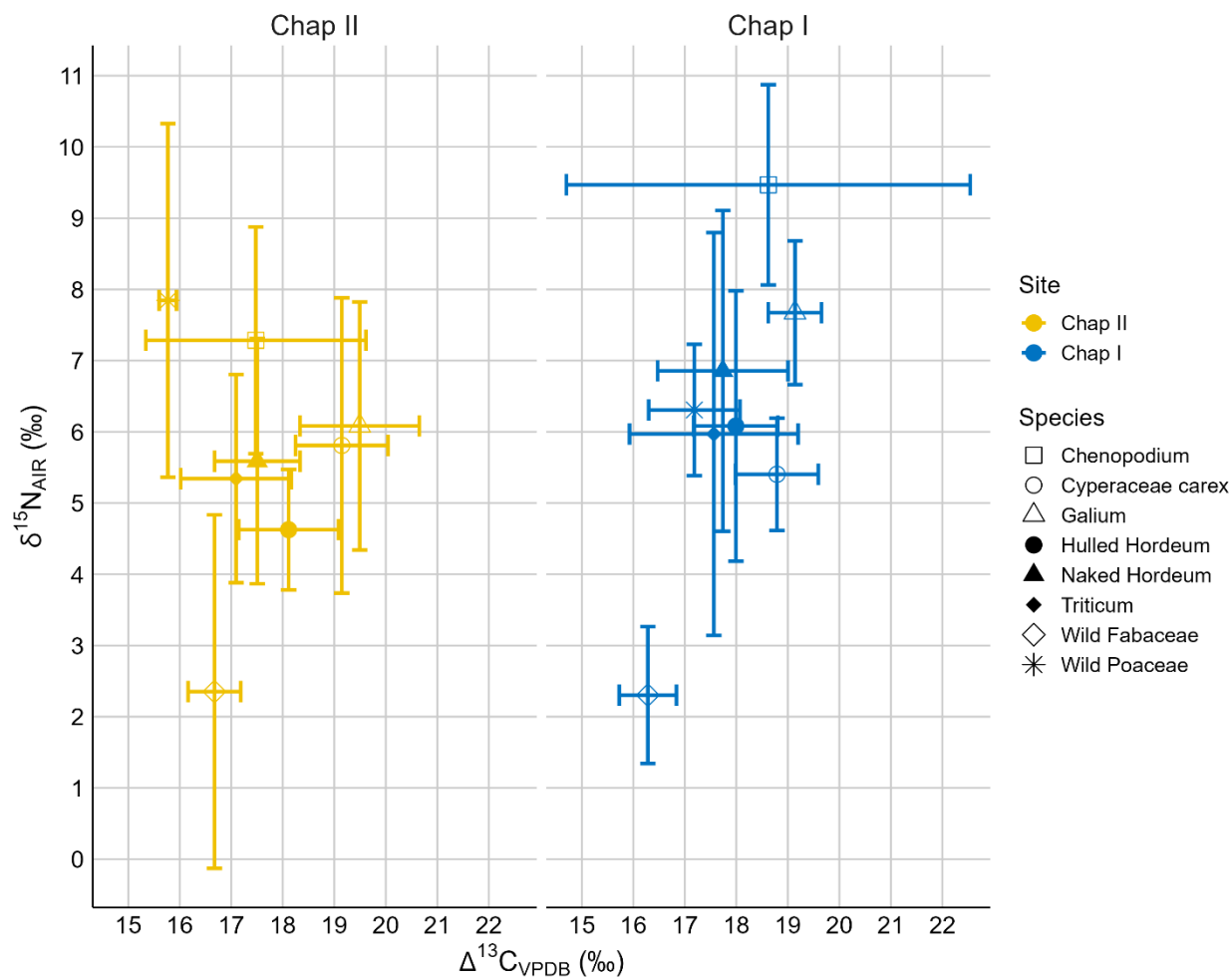


Figure 6. Scatter plot with means and standard deviations of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of domestic cereal grains and wild taxa from Chap II, left, and Chap I, right.

2.5 Discussion

The results of stable isotope analyses of archaeological seeds from Chap provide insight into shifting cultivation practices between the Bronze and Iron Ages in the mountainous region of Kyrgyzstan.

2.5.1 Diachronic and taxa-specific manuring strategies

The $\delta^{15}\text{N}$ values of the majority of wheat and barley grains for both Chap I and II are above the estimated natural baselevel, suggesting anthropogenic activities leading to ^{15}N enrichment is likely. Non-human related processes such as denitrification of water-logged soil, e.g. seasonal flooding, could also increase the $\delta^{15}\text{N}$ values of crop remains. However, if that was the main drive on a regional scale, I would expect the measured $\delta^{15}\text{N}$ values to be closer to the estimated herbivorous forage accounting for the diet-tissue offset.

There is a substantial increase in $\delta^{15}\text{N}$ values of barley grains over time while wheat $\delta^{15}\text{N}$ values remain relatively the same between the two occupational periods (Figure 3). This may indicate that cultivation practices for barley change through time, resulting in more ^{15}N enriched growing conditions for barley, but not for wheat. Moving cultivation plots in more arid or open soil conditions could result in higher plant $\delta^{15}\text{N}$ values (Szpak et al., 2013; Szpak, 2014), as well as the natural abundance of livestock manure if barley was now cultivated in pastureland previously unexploited by cultivation. The paleoclimate data suggest wetter and cooler conditions during the occupational phase of Chap I (Spate et al., 2022). It is not unreasonable to assume an uphill movement of barley cultivation during Chap I to pasturelands that were more arid and manure-rich relative to more-exploited lower lands could explain the observed trends. The faunal remains indicate a trend of increased reliance on pastoral activities over time, reinforcing the observation made isotopically. I may be seeing an integration of high-pasture cultivation of barley that coincides with increased transhumant pastoral activities during Chap I. Wheat, on the other hand, remains cultivated at the farmstead. These results resonate with those at Arslantepe, Turkey (4300–2000 BCE), where researchers found that barley had higher $\delta^{15}\text{N}$ values than wheat (Vignola et al., 2017). They suggest that the movement of barley cultivation

into marginal pastureland with newer soils that were previously less exploited than those closer to the settlement and had a higher availability of animal manure. Wheat continued to be cultivated in overexploited fields close to the settlement and possibly intercropped with legumes that would lead to ^{15}N depletion due to rhizobia nitrogen fixation.

An alternative explanation could be that barley received more manuring than wheat, during both Chap II and I, and the difference in manuring level became more pronounced in Chap II, perhaps due to a preference for barley. This scenario, however, counters trends observed elsewhere in Eurasia, where wheat was managed more intensively compared to barley due to its ecological hardness. This is the case in Neolithic Greece and Bronze Age China, as documented by Vaiglova et al. (2014a) and Li et al. (2022). Similarly, in southern Levant during the Early to Middle Bronze Age at Tel Kabri II (2900-1700 BCE), emmer wheat was the only manured crop, while barley, legumes, and grapes were likely not (Riehl, 2023). The differing trends in wheat and barley, for whatever reason, show the complexity of the cultivation systems that likely involved both cultural preference and taxa-specific management in a high-altitude environment.

2.5.2 Early evidence for anthropogenic watering of wheat and barley

Turning to $\delta^{13}\text{C}$ values as a proxy for water availability, during the earlier period, most of the wheat and barley grains are over the Optimal Watering Thresholds, suggesting that there is enough water provided to the plants to allow for stress-free growth (Figure 3). This water availability could be the result of irrigation, including alteration of existing waterways with small ditches or strategic planting in moister areas. To support such observation, ancient water management structures have been recorded geospatially in areas surrounding Chap, roughly correlated with other cultural features such as burial mounds and stone structure spanning the

Bronze Age to Turkic periods (Rouse et al., 2022). The abundance of sedges in the archaeobotanical assemblages at Chap I and II, which today are commonly found in irrigation ditches surrounding cultivation plots, lend additional support to anthropogenetic activities to adequately supply water to the cultivated crop. This observation was previously made based on archaeobotanical evidence (Motuzaite-Matuzeviciute et al., 2019b, 2020, 2021b) and attested with isotopes presented in this study.

There is a general increase in $\delta^{13}\text{C}$ values from Chap II to Chap I for both wheat and barley, with a substantial change in percentages of grains over the Superfluous Watering Thresholds (Figure 3, Figure 4). The incorporation of domesticated legumes and hulled barley during the later occupation phase also suggests a more complex cultivation system and the need for water management, as these are particularly water-demanding crops (Motuzaite-Matuzeviciute et al., 2019b). Overall, from the earliest occupation at Chap, the wheat and barley crops receive adequate water for optimal growth. For barley, this is interesting, as it is generally considered a more drought tolerant crop and often is grown in more water-stressed environments than wheat in Southwest Asia and East Asia alike (Riehl, 2008, 2009; Masi et al., 2014; Vignola et al., 2017; Li et al., 2022). The water availability for both wheat and barley at Chap increased over time, which was likely due to more intensive water-management systems that allowed for the multi-cropping system including wheat, hulled and naked barley, and domesticated peas.

We should however consider paleoclimate data regarding natural moisture levels. The Tien Shan mountains are situated at the intersection of the Atlantic Westerlies and the East Asian Monsoon, which causes a unique paleoclimate record, distinct from the broader patterns seen across Inner Asia. Spate et al. (2022), in their review of paleoclimate research of Inner Asia during the Holocene, find conflicting reports on the precipitation trends, which they attribute to

the regions sensitivity to both short and long-term changes in intensity of the Western and Asian summer monsoon systems and the mountainous topography affecting hydrology and the resulting paleoclimate proxies. To help clarify trends for the Kochkor region, they use *Artemisia*/Chenopodiaceae pollen ratios from Issyk Kol lake cores (Leroy and Giralt, 2021; Leroy, 2022) to plot localized precipitation trends. They find an overall drying period from 6000 – 3000 BP, with increasing moisture after 3000 BP. This roughly correlates with Leroy (2021), who analyzes various pollen taxa including *Picea*, *Cyperaceae*, *Artemisia*, and *Amaranthaceae* to identify a slightly wetter and cooler period from 4190 – 4010 BP which becomes more humid and cooler from 3300 – 2700 BP. The earlier, dryer period corresponds with occupation at Chap II, while the wetter and cooling corresponds with occupation at Chap I. While changing climatic conditions during Chap I could have contributed to increasing water availability on a landscape scale; in our view, the observed isotopic trend is best understood as a result of more localized community-rooted strategies.

2.5.3 Contextualizing growing conditions from wild taxa

Wild taxa from archaeobotanical assemblages are key sources of information that, when combined with the results of the stable isotope analysis, provide additional lines of evidence for understanding the agricultural systems in place at Chap I and II. I analyzed both the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of select arable weed taxa and proportions of habits of wild taxa as proxies for understanding broader ecological conditions around the Chap sites.

The depositional and taphonomic conditions could affect our interpretations of what these wild taxa represent. There are several common wild taxa, that when found with domesticate grains, are likely representative of harvesting and processing byproducts of the cereal grains. The

growing conditions of those wild taxa, if indeed they are arable weeds, could inform past field conditions. For example, *Carex* sp. (sedges) and *Juncus* sp. (rushes) commonly adapt to wetland conditions, such as those found in marshy landscapes, along river/streams, and in irrigation ditches. *Galium* sp. (bedstraw) and *Polygonum* sp. prefer open arable and meadow-like conditions that also have plentiful water availability. *Chenopodium* spp., along with *Galium* sp., enjoy disturbed, nitrogen rich soils and often grow in former domestic spaces or corrals. The presence of many of these taxa also could be the result of livestock foddering with agricultural byproducts and/or dung used as fuel and subsequently deposited into the stratigraphy through cooking and heating practices. Dung was likely used as manure, which would provide another source of weed seeds in cultivated fields. Carbonized sheep pellets were recovered in floatation samples from Chap I, but not from Chap II (Motuzaite-Matuzeviciute et al., 2019b, 2022b). While I cannot rule out dung-burning as a key taphonomic pathway, the presence of many wild taxa commonly associated with domesticated cereal crops suggests those weedy taxa were likely incorporated in assemblage through crop processing.

I can make generalized comparisons of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values across time for each taxon and how these relate to the wheat and barley trends. I am limited from further interpretation as experimental work on carbon fractionation in wild taxa has not yet been conducted. Nitrogen uptake should occur similarly across taxa, except for nitrogen fixers such as the wild Fabaceae (Fraser et al., 2011; Jensen et al., 2020). Interestingly, only mean $\delta^{13}\text{C}$ values of *Chenopodium* and wild Poaceae increased over time, following the same pattern as observed in wheat and barley samples (Figure 5, Figure 6). A possible interpretation is these plants were indeed arable weeds in the fields growing with wheat and barley cultivars. The *Carex* and *Galium* remain relatively stable through time, while the wild Fabaceae decrease through time. There could be a

variety of scenarios causing the observed trends including differences in seasonal growing conditions or locations, intra-variability within the cultivation plot, or, if the some of these seeds entered the archaeological record through dung burning, they may have grown in variable locations (stream edges vs. dryer meadows) before being consumed by livestock.

Chenopodium, *Galium*, and wild Fabaceae have increased mean $\delta^{15}\text{N}$ values through time, while *Carex* and wild Poaceae decrease (Figure 5). Such variability across wild taxa $\delta^{15}\text{N}$ values indicate heterogeneous pathways to the macrofossil assemblage. Riehl (2023) observed archaeological *Lolium* sp. seeds for $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ and found these weedy species were most aligned with trends observed in barley isotope values, potentially suggesting these were weeds of the barley field. If a similar mechanism applies to Chap, the only wild species that matches closely with the domesticated cereals is the wild Poaceae from Chap I, which is closely aligned with the values of wheat (Figure 6). More work is necessary to allow for the interpretation of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wild taxa at archaeological sites to inform the overall farming systems.

The habitats of wild taxa are also useful in interpreting the broader ecology surrounding sites and contextualizing the growing conditions of cereal crops (Jones et al., 1999; Jones, 2002; José-María et al., 2010; Carmona et al., 2020). In particular, percentages of water-demanding plants, such as sedges and rushes, can reflect irrigation practices and availability of moist soils (Moore et al., 2000; Miller, 2010; Miller and Marston, 2012a). Likewise, ruderal taxa grow well in disturbed, often N enriched and wet soils, and are generally found in and around human occupations and crop fields. Grassland taxa enjoy open, semi-arid meadows or steppe-like habitats. When comparing the percentages of each habitat type to $\Delta^{13}\text{C}$ values of cereal crops, there is an increase in wetland taxa from Chap II to Chap I (Figure 7, Supplementary Table 7).

This further supports a transition to a more irrigated agricultural system coupled with the more humid and cool climate shift that occurs during Chap I occupation (Spate et al., 2022).

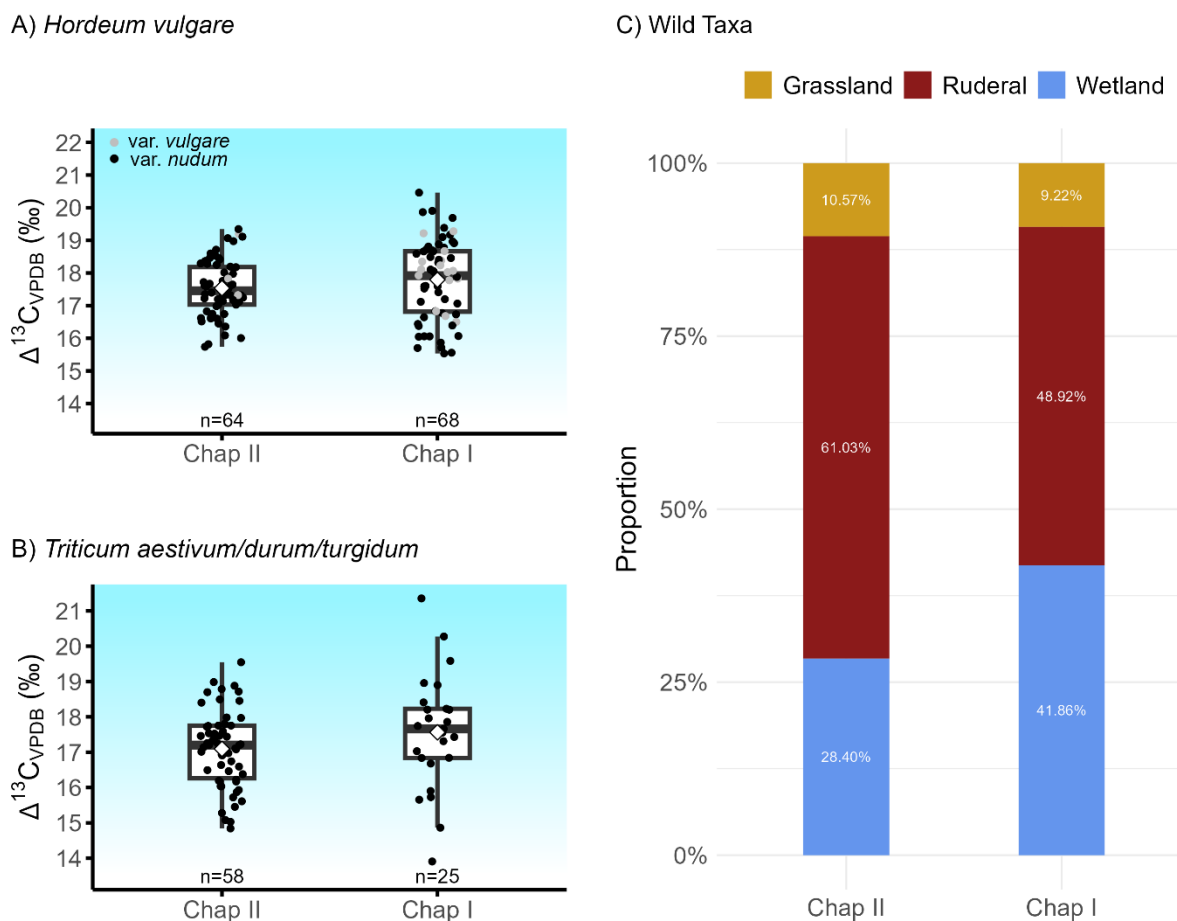


Figure 7. Boxplots presenting $\Delta^{13}C$ isotope results through time of A) *Hordeum vulgare* and B) *Triticum aestivum/durum/turgidum*. C) Bar chart presenting change in proportion of wild taxa by habitat type through time.

2.5.4 Contextualizing Chap cultivation within the IAMC

The results show a complex cultivation strategy for wheat and barley that is established during the first occupation of the site, Chap II, during the 3rd millennium BCE and continues into the 2nd millennium BCE during occupation of Chap I. The increase in water availability and soil

fertility, as seen through the $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wheat and barley grains, and the introduction of broomcorn millet and pea cultivation during the Chap I occupation indicate increasingly complex agricultural practices (Motuzaite-Matuzeviciute et al., 2021b). This is coupled with evidence for more specialized use of domestic livestock, with a focus on secondary products and draft labor from cattle and horses and specialized wool production from sheep (Ananyevskaya et al., 2021).

This intensification of agropastoralism differs from trends seen in other parts of the Inner Asian Mountains. For example, at Shirengigou in Eastern Tien Shen, there is a decrease in intensification signatures in wheat and barley grains that correlates with an increase in nomadic pastoralism practices in the region (Tian et al., 2022). This transition occurs between two occupation phases, 1300-800 BCE and 400 BCE to 300 CE, which chronologically overlap and follow the occupation at Chap II (*ca* 1000 – 800 BCE). At the site of Tasbas from the Bronze to Iron Ages (*ca* 1500 BCE – 300 CE), as presented in the following chapter, there is a clear decrease in $\delta^{15}\text{N}$ values of barley through time. However, there is a diachronic intensification signature in water availability for the wheat grains (but not barley, which remain stable). When comparing these trends across the IAMC, they could reflect a broader transition to more extensive nomadic pastoralism from the Late Bronze to Iron Age after an initial intensification in the Early and Middle Bronze Ages, or a more localized choices and context-dependent decision making across Asian environments. Further work on other assemblages in the IAMC, both geographically and temporally, will help clarify these trends.

2.6 Conclusion

In this study, I presented $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wheat and barley grains from the Bronze Age, mountainous agropastoral site of Chap I and II. Results indicate an investment in plant cultivation, through the use of watering and manuring, from the earliest occupation at the site. There is growing investment in cultivation through time, as indicated by increasing $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. However, there are differences in the treatment of wheat and barley. While barley grains increased in $\delta^{15}\text{N}$ through time, wheat grains did not. Further, barley was likely grown in a dryer system than wheat. These results resonate with similar findings in the Levant and eastern Tien Shen mountains, where differential treatment of wheat and barley are also recorded, though these differences manifest in a variety of ways. I exploratively analyzed the stable isotope values of common arable weeds at Chap and found a complicated pattern through time that did not always match up with the cereal results. Nonetheless, the cereal grain watering signatures were further supported by a paleoecology analysis using percentages of wild taxa habitats. While agriculture is traditionally seen as secondary in agropastoral systems, the Bronze Age agropastoralists at Chap integrated an intensive cultivation system with transhuman pastoralism to succeed in the high mountains of the Tien Shen.

What is clear across these new isotopic datasets that analyze crop cultivation strategies within pastoral landscapes is an initial dedicated labor system assigned to crop cultivation. Agropastoralists incorporated watering and manuring practices, often treating crops differently and creating complex multi-cropping systems, that allowed for the successful integration of cultivation into an extensive agropastoral subsistence strategy. While the knowledge of cultivation techniques of these crops seems to have initially travelled with them from their

centers of domestication, the mountain communities localized these strategies to best fit their social, economic, environmental, and labor systems. This parallels a similar decoupling of grains from culinary traditions seen in wheat and barley as it move eastward, and broomcorn and foxtail millet on their journey west (Liu et al., 2016a; Ritchey et al., 2022; Sun et al., 2024). Continued research that traces the nuances of plant cultivation across Inner Asia will further clarify or complicated these broad regional trends.

2.7 References

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Chapter 3:

Cultivation strategies at Tasbas, Kazakhstan,

from the Bronze to Iron Ages

3.1 Introduction

Archaeological investigations into agropastoralism in mountainous Inner Asia provide intriguing data regarding ancient economic and subsistence approaches that exemplify the range of productive strategies employed. Specifically, communities occupying the Inner Asian Mountain Corridor (IAMC, the foothills, mountain valleys and mountains of Inner Asia, primarily those of the Dzhungar, Tianshan, and Altai Mountain ranges) during the Bronze and Iron Ages (3rd-1st millennium BCE) developed specific multi-resource subsistence strategies to succeed in these highly-variable environments with short frost-free seasons and bitterly cold winters (Frachetti, 2012; Outram et al., 2012; Spengler et al., 2014a; Chen et al., 2015; Lu, 2016; Hermes et al., 2019; Schmaus et al., 2019; d’Alpoim Guedes and Aldenderfer, 2020; Song et al., 2021; Motuzaite-Matuzeviciute, 2024). While there has been considerable recent momentum towards understanding the animal-based subsistence and pastoralism in mountainous Inner Asia, this paper investigates the plant side of the story. I use a combined archaeobotanical and plant stable isotope approach to investigate how cultivation was incorporated into the agropastoral system at the Bronze and Iron Age site of Tasbas in eastern Kazakhstan. The success of such integrated multi-resource agropastoralism at Tasbas and other sites in the IAMC likely contributed to the trans-Eurasian exchange of technologies, material traditions, cultigens, and livestock during the Bronze and Iron Ages (Jones et al., 2011, 2016a; Frachetti, 2012; Spengler et al., 2016; Stevens et al., 2016; Liu et al., 2019). The results indicate that the Tasbas domestic crop complex

includes free-threshing wheat (*Triticum cf. aestivum*), barley (*Hordeum vulgare*), broomcorn (*Panicum miliaceum*) and foxtail (*Setaria italica*) millet, and green peas (*Pisum sativum*). This cultivation system was supported by a variable watering and soil-enrichment (manuring) system that provided taxa-specific investment in crops that changed over time.

The agropastoral evidence at Tasbas in the Dzhungar mountains of Kazakhstan contributes to our understanding of prehistoric food globalization processes, which traces the movement of domesticated crops and livestock across Eurasia between the 5th and 2nd millennium BCE (Jones et al., 2016b). The idea of ‘*food globalization*’ in deep history has generated a fair amount of scholarly debate regarding the concept as well as the driver (Boivin et al., 2012; Liu and Jones, 2014; Jaffe and Flad, 2018). Nonetheless, the archaeological evidence for the routes and chronology of this exchange are now well established (see 1.1 Prehistoric Food Globalization for a discussion), prompting further questions regarding how communities negotiated labor budgets to adopt non-native crops and livestock into new physical and cultural environments (Vaiglova et al., 2021; Tian et al., 2022). For example, a recent study illustrated that the eastern dispersal of wheat (*Triticum cf. aestivum*) into ancient China was accompanied by water management and soil preparation systems that originated in the Fertile Crescent (Li et al., 2022). Barley (*Hordeum vulgare*), on the other hand, was folded into the eastern dry land farming systems. Not only did crops face new agriculture systems, but also new cuisines, which enacted certain selective pressures of novel crops to fit the new culinary systems across Eurasia (Liu et al., 2016a; Ritchey et al., 2022; Sun et al., 2024). Building on these recent developments, this paper explores how communities organized labor to negotiate the time and effort of plant cultivation in a landscape with a more enduring history of animal husbandry. Was the introduction of non-indigenous domesticated crops in the IAMC accompanied by labor-intensive

cultivation strategies, or did communities modify cultivation techniques to fit a more extensive agropastoral lifestyle characteristic of mountainous mobile pastoralism?

Macrobotanical remains and plant stable isotopes provide complimentary data for understanding ancient cultivation strategies. I combined newly excavated macrobotanical data from the 2023 field season with previously analyzed data from excavations at Tasbas in 2011 (Spengler et al., 2014b; Doumani et al., 2015) to reconstruct the crop assemblage at Tasbas from the Bronze to Iron Ages. Further, I present new carbon and nitrogen stable isotope results of free-threshing wheat, barley, green pea, and a variety of wild taxa to directly assess the water availability and soil enrichment of the plant remains at Tasbas. Together, these data expose diachronic changes in plant cultivation and associated labor practices and provide baseline information about ancient diets that impact interpretation of previous and future paleodietary reconstructions in the region. The results indicate that the Tasbas domestic crop complex of free-threshing wheat, barley, broomcorn and foxtail millet, and green peas was established by the Middle Bronze Age, with barley becoming the primary crop in the Late Bronze Age to Early Iron Age. This cultivation system was supported by watering and manuring activities providing taxa-specific care for crops that varied over time.

3.1.1 Archaeology at Tasbas

Tasbas sits between large granite boulders and a seasonal stream, along a southward slope that faces the Dzhungar Alatau at 1500 meters above sea level (masl hereafter). First pilot excavations in 2001 were led by the Margulan Institute of Archaeology Kazakhstan, in Almaty, and identified evidence for Bronze and Kazakh period occupation (Mar'yashev, 2002).

Following excavations identified similar Bronze Age occupation layers at new excavations at Tasbas in 2011 and Begash in 2005 and 2006 (Frachetti and Mar'yashev, 2007; Spengler et al.,

2014c; Doumani et al., 2015). Comprehensive data analysis of ceramics, lithics, fauna, flora, and phytoliths from Tasbas show evidence for early ritual activity, followed by a mixed mobile pastoralist economy that integrated agriculture to support a multi-season residence (Doumani et al., 2015). Radiocarbon dates and ceramic typologies show multiple occupation periods at Tasbas that span the 3rd to 1st millennium CE. Faunal remains are dominated by domestic livestock (92 % of assemblage), including sheep/goats (*Ovis/Capra*), cattle (*Bos tarus*), horse (*Equus caballus*), ass (*Equus asinus*), and camels (*Camelus*). Diachronically, caprines (sheep/goats) decrease in time as use of cattle and horses increase (Supplementary Figure 6). Analysis of the ceramic assemblage shows a local, hand-made tradition utilizing slab-coil or slab-mold construction, with some ceramics showing evidence of textile-lined molds (Doumani and Frachetti, 2012; Doumani et al., 2015). The ceramic production techniques contain a lot of internal variation in modes of paste preparation and choices in how to style and decorate vessels (Doumani Dupuy, Amicone et al. in press). The macrobotanical remains reveal Early Bronze Age ritual use of wheat at Tasbas, followed by evidence of local cultivation of predominately barley, with some wheat, green peas, and broomcorn and foxtail millet in the 2nd millennium BCE onward (Spengler et al., 2014c, 2014b; Doumani et al., 2015).

In 2023, the team returned to the site to expand the excavation areas from the previous field seasons and identify early occupation layers. These new occupation horizons contained domestic structures, cooking installations, hearth features, and human burials. Table 3 presents the 2011 archaeological phases and newly assigned horizons from the 2023 excavation, radiocarbon dates and associated archaeological periods.

Table 3. Archaeological phases from the 2011 and 2023 seasons and associated cultural phases and calibrated AMS dates. The Final Bronze Age/Early Iron Age transition is categorized as Final Bronze Age for analyses in this paper. Grey rows with * denote new C-14 dates from the 2023 season. Date for Late Iron Age¹ from Doumani Dupuy et al. (2024). Remaining dates are from the 2011 excavation and reported in Doumani (2015).

2011 Phases	2023 Horizons	Archaeological Period	Date BP	Calibrated date BCE	
				68.3 % probability (1 σ)	95.4 % probability (2 σ)
1	5	Early Bronze Age	4100 $\pm$ 30 4060 $\pm$ 30	2620 – 2500 cal. BCE	2832 – 2492 cal. BCE
	4	Middle Bronze Age	3548 $\pm$ 19*	1931 – 1828 cal. BCE	1951 – 1775 cal. BCE
2a	4	Late Bronze Age	3670 $\pm$ 45 3150 $\pm$ 35 3090 $\pm$ 40 3030 $\pm$ 35	1408 – 1304 cal. BCE	1416 – 1287 cal. BCE
2b	4	Final Bronze Age	2930 $\pm$ 30 2940 $\pm$ 30	1194 – 1088 cal. BCE	1208 – 1054 cal. BCE
3	4	Final Bronze/Early Iron Age transition	2720 $\pm$ 35	898 – 830 cal. BCE	930 – 806 cal. BCE
	3	Early Iron Age	2521 $\pm$ 17*	774 – 590 BCE	778 – 550 cal. BCE
	2	Late Iron Age	1840 $\pm$ 25* ¹	132 – 241 cal. CE	126 – 304 cal. CE
4	1	Kazakh Period (Historical)			

3.1.2 Plant stable isotope principles

Stable isotope analyses of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of archaeological plant remains provide information regarding the plants' growing conditions. $\delta^{13}\text{C}$ values infer water availability during cultivation (Farquhar et al., 1989; Araus et al., 1997, 1999a; Wallace et al., 2013). $\delta^{15}\text{N}$ values allow for the assessment of soil ^{15}N enrichment during plant growth (Bogaard et al., 2007; Fraser et al., 2011; Styring et al., 2018). Natural and cultural factors influence these measurable values and experiments provide guidelines for interpreting the role of anthropogenic activities on growing conditions (see following discussions). Together, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values allow for a direct assessment of ancient strategies of water and soil maintenance and has been used to investigate early agricultural management in the Middle East, Europe, East Asia (Bogaard et al.,

2013; Vaiglova et al., 2014a; Styring et al., 2016b; Li et al., 2022) and recently in Inner Asia (Tian et al., 2022; Ritchey et al., 2024).

The $\delta^{15}\text{N}$ values of historical natural vegetation are unknown but can be estimated by accounting for diet-tissue isotopic offset using mean $\delta^{15}\text{N}$ values of archaeological wild herbivores, which subsisted largely on natural vegetation in the given environment. The trophic offset is approximately 3-5 ‰ for collagen (difference between diet and consumer tissue in $\delta^{15}\text{N}$), varying according to taxonomy of consumers and diets (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Hedges and Reynard, 2007). For the Tasbas environment, Hermes et al. (2019) provide collagen $\delta^{15}\text{N}$ values of archaeological animals from Bayan-Zhurek Valley, dated to *ca.* 2700 BCE – 30 CE. The mean $\delta^{15}\text{N}$ of wild herbivores (red deer, ibex, and wild sheep) is 5.7 ± 1.3 ‰, $n = 31$. If this represents nitrogen isotope ratios resulting from foraging natural vegetation in the broader Tasbas environment during the time of occupation, the baselevel can be estimated as $0.7 - 2.7$ ‰, accounting for the $3 - 5$ ‰ trophic difference.

To interpret $\Delta^{13}\text{C}$ values of archaeological grains, I use Li et al. (2022)'s watering thresholds developed based on the experimental thresholds provided by Wallace et al. (2013), where $\Delta^{13}\text{C}$ values below the Optimal Watering Threshold (OWT) suggest water availability limited plant growth, values above the OWT suggest water availability that did not limit plant growth, and values above the Superfluous Watering Threshold (SWT) suggest water availability well above the plant's need. Due to taxonomic differences in carbon fractionation, barley has an OWT of 17 ‰ and a SWT of 18.5 ‰ and wheat a OWT of 16 ‰ and SWT of 17 ‰. For the peas, I use Wallace et al. (2013) thresholds for lentils and assigned an OWT of 15 ‰ and SWT of 17 ‰ based on their original divisions between poorly, moderately, and well-watered values. See section 1.3 Plant Stable Isotope Principles for an in-depth discussion.

The archaeological grains I analyzed are charred which occurred through exposure to high temperatures and possibly directly to fire, which chemically altered the seeds by removing water vapor and volatile organics. Overall, the grain maintains its stable carbon and nitrogen isotope composition through this charring process, albeit with known offsets, which varies with the temperature and duration of charring. These offsets, averaged across temperatures and duration, are + 0.11 ‰ $\delta^{13}\text{C}$ and + 0.33 ‰ $\delta^{15}\text{N}$ (Nitsch et al., 2015). These are lower than the conservative 1 ‰ uncertainty used in many paleodietary studies (Fraser et al., 2013) and thus, should have little impact on data interpretation. Other diagenesis processes, such as soil bacterial activities, could cause post-depositional isotopic alterations on $\delta^{15}\text{N}$ values, but seem to have little effect in carbonized grains (DeNiro and Hastorf, 1985; Hartman et al., 2020). Nonetheless, it is still important to consider the potential offsets, especially when reconstructing past agricultural practices with comparison to modern isotopic experiments.

3.2 Materials and Methods

I used R (version 3.4.1) packages ggplot, EnvStats, and esci to create graphs and perform statistical analyses. I used Jamovi (Version 2.4.11) to calculate confidence interval statistics and plots.

3.2.1 Macrobotanical materials and analysis

I present here macrobotanical results from the 2023 excavation at Tasbas which expands our understanding of domesticated plant cultivation at the site spanning the Early Bronze Age (EBA), Middle Bronze Age (MBA), Late Bronze Age (LBA), Final Bronze Age (FBA), Early Iron Age (EIA), and Late Iron Age (LIA) (Table 3). During excavation, the team collected

flotation samples from discrete contexts that showed evidence of charring, domestic activity, and ritual activity. 36 samples, averaging 7.5 liters of sediment, were floated using bucket flotation, air dried, and stored. I used a fine chiffon mesh for collecting light fractions and a 1.4 mm geological sieve for heavy fractions. At Nazarbayev University in Astana, Kazakhstan, I analyzed the light and heavy fractions for macrobotanical remains, using published articles and guides as reference (Netherland Seed Atlas, Flora of China). I followed Spengler 2013's sorting procedures: light and heavy fractions were weighed, heavy fractions scanned for macrobotanical remains, faunal remains, and artifacts, and light fractions were separated with USGS geological sieves with sizes 2.0 mm, 1.0 mm, 0.5 mm, 0.35 mm. Material smaller than 0.35 mm was collected in the pan and was scanned but not extensively analyzed. Remains such as wood charcoal, thorns, dung, ash, mudbrick, culms, and various plant fragments were collected from >2mm sieve. Charcoal and dung were mostly counted and weighed, but for some samples due to abundance, only were weighed. Due to time constraints for analysis, I was not able to thoroughly distinguish and quantify hulled and naked barley varieties; the Bronze Age samples did not have any clear hulled barley present, but the Late Iron Age samples did have a number of hulled barley grains (see Supplementary Figure 11 for example image). For now, I label all barley as *Hordeum vulgare* from the 2023 season. In the future, I will complete this analysis when time and funding permits.

3.2.2 Isotopic analysis of archaeological seeds

I selected cereal grains, peas, and wild taxa from the 2011 and 2023 excavations for isotopic analysis. For the wheat and barley, I followed Vaiglova et al. (2022) and Stroud et al. (2023a)'s guidelines for assessing the charring conditions of grains to ensure recovery of isotopic values. Through visual analysis of seed coat preservation, morphology, and internal matrix composition,

I classified wheat and barley grains into “good”, “borderline”, and “poor” categories (Supplementary Figure 1). Although there are no comparative studies for legumes at this time, I cross-sectioned the peas to inspect their matrix. All peas had robust, good matrices. In their experiments, Stroud et al. (2023a) find that there is variation of isotope value across charring conditions in cereal grains. Thus, I compared my classifications against associated $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values to assess any potential effect of grain condition on isotopic composition. Visual inspection of the results indicates no substantial patterns in isotopic value between charring status classifications (Figure 8, Supplementary Table 12). I estimated the 95 % confidence intervals (CIs, reported as [lower level, upper level]) of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ means of each charring condition group (Supplementary Table 12, Supplementary Figure 7). The mean values and CIs are nearly identical across the charring conditions for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. For $\delta^{13}\text{C}$, the calculated group means are good 17.4 ‰ [17.0, 17.8], n = 49, borderline 17.7 ‰ [17.0, 18.4], n = 19, and poor 17.7 ‰ [17.2, 18.3], n = 27, and for $\delta^{15}\text{N}$ good 6.1 ‰ [5.3, 6.8], borderline 5.9 ‰ [4.7, 7.1], and poor 5.9 ‰ [4.9, 6.9]. Due to the lack of variation between charring condition categories, I use all isotopic measurements regardless of grain condition.

I ran single-grain analyses for all wheat, barley, and peas. I combined multiple seeds from the same flotation sample and/or context (ranging from 3-36) for the smaller wild taxa to ensure adequate mass (Supplementary Table 13). After assessing grain preservation status, I prepared grains and wild seed samples for isotopic analyses following Vaiglova et al. (2014b)’s pretreatment protocol. I cleaned each seed of any visible surface contaminants and crushed them to a fine powder. I then used a gentle acid wash to remove an exogenous soil carbonate from the sample by soaking each sample with 0.5 M hydrochloric acid heated at 80 °C for 30 minutes. After three washes with deionized water, I dried each sample in a vacuum freezer for eight hours.

I weighed out 900 μg of the dried samples and placed them into tin capsules. I conducted the carbon and nitrogen stable isotope analyses using an Elemental Analyzer coupled to a Thermo Delta V Plus Continuous Flow Isotope Ratio Mass Spectrometer (EA–IRMS) housed at the Department of Earth, Environmental, and Planetary Sciences at Washington University in St. Louis, USA. I normalized the raw $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values relative to VPDB and AIR, respectively, with the international standards of USGS 40 ($\delta^{13}\text{C} = -26.4 \text{ ‰}$, $\delta^{15}\text{N} = -4.5 \text{ ‰}$) and USGS41a ($\delta^{13}\text{C} = +36.6 \text{ ‰}$, $\delta^{15}\text{N} = 47.6 \text{ ‰}$), and urea ($\delta^{13}\text{C} = -45.4 \text{ ‰}$, $\delta^{15}\text{N} = -0.9 \text{ ‰}$). We used two in-house standards for linearity and check standards: acetanilide ($\delta^{13}\text{C} = -29.5 \text{ ‰}$, $\delta^{15}\text{N} = +47.6 \text{ ‰}$) and BR millet (Bob’s Red Mill millet flour; $\delta^{13}\text{C} = -13.2 \text{ ‰}$, $\delta^{15}\text{N} = +3.3 \text{ ‰}$). 9 replicates were conducted to aid in assessing precision and accuracy. Averaged values of these replicates are used in the results and analyses. Precision ($u(Rw)$) was determined to be $\pm 0.36 \text{ ‰}$ for $\delta^{13}\text{C}$ and $\pm 0.24 \text{ ‰}$ for $\delta^{15}\text{N}$. Accuracy or systematic error ($u(bias)$) was determined to be $\pm 0.25 \text{ ‰}$ for $\delta^{13}\text{C}$ and $\pm 0.29 \text{ ‰}$ for $\delta^{15}\text{N}$ based on calibration standard and check standard measurements. Using the equations from Szpak et al. (2017), the total analytical uncertainty was determined to be $\pm 0.44 \text{ ‰}$ for $\delta^{13}\text{C}$ and $\pm 0.38 \text{ ‰}$ for $\delta^{15}\text{N}$.

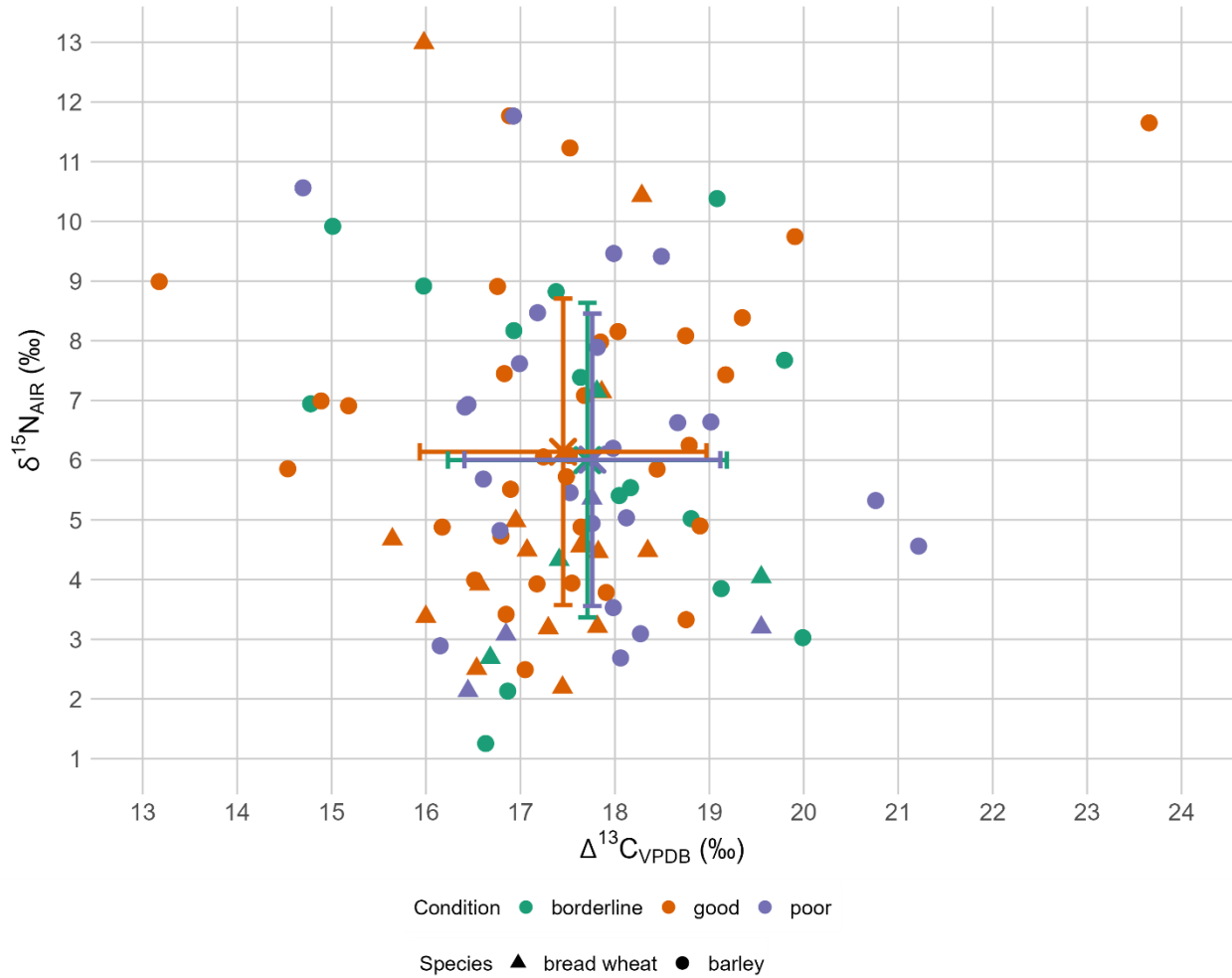


Figure 8. Scatter plot of $\delta^{15}\text{N}$ and $\Delta^{13}\text{C}$ values of free-threshing wheat (circles) and barley (triangles) grains grouped by their qualitatively assigned charring condition: good (orange), borderline (green), and poor (purple). Superimposed are the mean and standard deviations of each charring status.

3.3 Results

3.3.1 Macrobotanical results

Results from the 2023 excavation

I present here the macrobotanical analyses of the 2023 excavations at Tasbas. From 36 flotation samples, representing 27 contexts, 9,071 seeds and seed fragments were identified (Table 4 and Table 5, Supplementary Table 9). 1,328 seeds/fragments are domesticated taxa, and 7,713 seeds

are wild taxa. Other than a few unique ritual deposits, most contexts sampled are reflective of domestic activities, including firepits, burn layers, floors/surfaces, and refuse remains. Domesticated taxa include *Hordeum vulgare* (n = 159 whole, 2 fragments), cf. *Triticum aestivum/durum* (n = 78 whole, 1 fragment), indeterminate *Cerealia* (n = 19 whole, 447 fragments), *Panicum miliaceum* (n = 279 whole, 3 fragments), *Setaria italica* (n = 122 whole, 1 fragment), and *Pisum sativum* (n = 25 whole, 5 fragments). 760 crop processing byproducts were identified, including the rachises of *Triticum aestivum* (n = 38) and *Hordeum vulgare* (n = 22). Of the total domesticate taxa assemblage (whole grains and fragments combined), *Cerealia* make up 53 %, *Panicum miliaceum* 32 %, indeterminate millet grain 24 %, *Hordeum vulgare* 18 %, *Setaria italica* 14 %, *Triticum aestivum/durum* 9 %, and *Pisum sativum* 3%. Measurements of barley and free-threshing wheat grains are presented in Supplementary Table 10 and broomcorn millet and foxtail millet in Supplementary Table 11. The wild taxa assemblage is dominated by *Chenopodium* spp. (n = 2,574), *Medicago/Trifolium/Melilotus* (n = 1,561), Cyperaceae *carex* (n = 533), and various grasses (n = 755), including *Bromus* sp., *Digitaria* sp., *Panicoid*-type, and *Stipa*-type. Images of representative macrobotanical remains are presented in Figure 9.

Through time, there are changes in the domesticate assemblage composition from the 2023 excavations. In the Middle Bronze Age, broomcorn millet and free-threshing wheat were the primary cultivars, followed by foxtail millet, and a lone barley grain. One whole cf. *Pisum* and 4 fragments were recovered, but the preservation of the seeds limits clearer identification to species and domesticated status. The domesticate assemblage, comprising of free-threshing wheat, barley, broomcorn and foxtail millet, and identifiable green peas is maintained into the Late Bronze, Final Bronze, and Early Iron Ages, with barley becoming the dominate domestic cereal. The Late Iron Age samples, from a unique burial context, are dominated by broomcorn

and foxtail millet. The Kazakh period sample has very few seeds recovered and no domesticates. Byproducts of crop-processing are present in the 2023 Tasbas samples (Figure 9 A, F, G, H, J), appearing first in the Late Bronze Age samples and continuing into the Early Iron Age samples. These include barley rachises and the remains of awns, palea/lemma, culms or nodes, and indeterminate spikelet forks/rachis. In the Early Iron Age free-threshing bread wheat rachises are present. The bread wheat rachises have the typical “shield shape” characteristic with the widest part just above the middle portion, a little to no swelling below the glumes (Jacomet, 2006). Further work will clarify the particular varieties of other rachises present at Tasbas.

Table 4. 2023 field season macrobotanical results from the Middle Bronze Age to the Final Bronze Age.

Time Period	Middle Bronze Age				Late Bronze Age				Final Bronze Age			
	n	ρ	%	u	n	ρ	%	u	n	ρ	%	u
Liters floated:	16.25				37.50				11.75			
Total seed count:	568				2509				2538			
Total contexts:	2				7				3			
Taxa	n	ρ	%	u	n	ρ	%	u	n	ρ	%	u
Domesticated												
Poaceae												
<i>Hordeum vulgare</i>	1	0.06	0%	50	36	0.96	1%	42.86	82	6.98	3%	100.0
<i>Hordeum vulgare</i> (rachis)					1	0.03	0%	14.29	13	1.11	1%	66.67
<i>Hordeum vulgare</i> (fragments)									1	0.09	0%	33.33
<i>Triticum aestivum/turgidum</i>	13	0.80	2%	100	18	0.48	1%	57.14	18	1.53	1%	66.67
<i>Panicum miliaceum</i>	39	2.40	7%	100	28	0.75	1%	28.57	12	1.02	0%	66.67
<i>Panicum miliaceum</i> (fragments)	2	0.12		50								
<i>Setaria italica</i>	8	0.49	1%	100	40	1.07	2%	57.14	5	0.43	0%	33.33
indeterminate millet grain	7	0.43	1%	100	60	1.60	2%	71.43	29	2.47	1%	100.00
<i>Cerealia</i>	3	0.18	1%	50	2	0.05	0%	14.29	8	0.68	0%	100.00
<i>Cerealia</i> (fragments)	14	0.86	2%	100	96	2.56	4%	71.43	220	18.72	9%	100.00
culm or node					45	1.20	2%	85.71	15	1.28	1%	66.67
palea/lemma					4	0.11	0%	28.57				
Spikelet Fork					4	0.11	0%		9	0.77	0%	66.67
Awn					3	0.08	0%	28.57	144	12.26	6%	33.33
Fabaceae												
<i>Pisum sativum</i>					17	0.45	1%	14.29				
cf. <i>Pisum</i>	1	0.06	0%	50								
cf. <i>Pisum</i> (fragments)	4	0.25	1%	50					2	0.17	0%	33.33
Domesticated Totals:												
Total Cereals (seeds + fragments)	87	5.35	15%		280	7.47	11%		375	31.91	15%	
Total Legumes (seeds + fragments)	5	0.31	1%		17	0.45	1%		2	0.17	0%	
Total Domesticates (Cereals + Legumes)	92	5.66	16%		297	7.92	12%		377	32.09	15%	
Total processing byproducts					57	1.52	2%		181	15.40	7%	

Table 4. Continued (page 2 of 3)

Wild									
Aliaceae									
<i>Alium</i> sp.			3	0.08	0%	14.29			
Asteraceae			103	2.75	4%	57.14	56	4.77	2%
<i>Artemisia</i> sp.									66.67
Amaranthaceae									
<i>Cheno-ams</i>	25	1.54	43	1.15	2%	42.86	337	28.68	13%
<i>Chenopodium</i> spp.	126	7.75	752	20.05	30%	100.00	162	13.79	6%
<i>Amaranthus</i> sp.	7	0.43	30	0.80	1%	42.86	36	3.06	1%
Brassicaceae									100.00
<i>Thlapsi arvense</i>			1	0.03	0%	14.29			
Caryophyllaceae									
<i>Vaccaria/Saponaria</i>			69	1.84	3%	28.57	196	16.68	8%
Caryophyllaceae	5	0.31	2	0.05	0%	28.57			100.00
Cyperaceae									
Cyperaceae spp.	1	0.06	8	0.21	0%	42.86	3	0.26	0%
<i>Carex</i> spp.	1	0.06	6	0.16	0%	28.57	3	0.26	0%
Poaceae									
<i>cf. bromus</i>			1	0.03	0%	14.29			
<i>cf. digitaria</i>	6	0.37	8	0.21	0%	28.57			
<i>Panicoid-Type</i>			77	2.05	3%	57.14	22	1.87	1%
<i>Poaceae</i> spp.	4	0.25	7	0.19	0%	28.57			66.67
<i>Pooid-Type</i>	1	0.06	9	0.24	0%	28.57	10	0.85	0%
<i>Setaria</i> (cf. <i>viridis</i>)			12	0.32	0%	28.57	16	1.36	1%
<i>Stipa-Type</i>	1	0.06	36	0.96	1%	71.43	18	1.53	1%
Fabaceae									66.67
<i>cf. Astragalus</i>			1	0.03		14.29			
<i>cf. Medicago/Trifolium/Mellilotus</i>	64	3.94	179	4.77	7%	100.00	48	4.09	2%
Fabaceae spp.			1	0.03	0%	14.29	1	0.09	0%
<i>Trifolium</i>							2	0.17	0%
<i>Trigonella-Type</i>			1	0.03	0%	14.29	1	0.09	0%
									33.33

Table 4. Continued (page 3 of 3)

<i>Vicia</i> sp.				1	0.03	0%	14.29	
Malvaceae								
<i>Malva</i> (cf. <i>sylvestris</i>)				1	0.03	0%	14.29	
Plantaginaceae								
<i>Plantago</i> sp.				1	0.03	0%	14.29	
Polygonaceae								
Polygonaceae spp.				3	0.08	0%	28.57	
<i>Polygonum</i> (<i>persicaria</i> -Type)				1	0.03	0%	14.29	3
<i>Polygonum</i> spp.				26	0.69	1%	42.86	2
<i>Rumex</i>				8	0.21	0%	71.43	7
Rosaceae								
<i>Fragaria/Potentilla</i>				51	1.36	2%	85.71	25
Rubiaceae								
<i>Galium</i> sp.				3	0.08	0%	28.57	1
Solanaceae								
<i>Hyoscyamus niger</i>				4	0.11	0%	42.86	
Solanaceae								
Verbenaceae								
<i>Veronica</i>				2	0.17	0%		2
Unknown								
unidentified plant fragments								
Unidentified Seed				56	1.49	2%	71.43	90
Other								
eggshell fragment								
plant Fibers								
Thorn				1	0.03		14.29	16
wood (>2.00mm) ct.								1
wood (>2.00mm) wt. (g)				26.09	0.70			72
bone (>2mm) ct.				3	0.08		14.29	37.64
Dung (>2mm) ct.				19	0.51		28.57	
ash >2mm wt. (g)								0.62

Table 5. 2023 field season macrobotanical results from the Middle Bronze Age to the Final Bronze Age.

Time Period	Early Iron Age			Late Iron Age			Kazakh Period			Grand Total		
Liters floated:	192.00			4.00			8.50			270		
Total seed count:	5209			1488			29			13603		
Total contexts:	13			1			1			27		
	n	ρ	%	u	n	ρ	%	u	n	ρ	%	u
Domesticated												
Poaceae												
<i>Hordeum vulgare</i>	40	0.21	1%	46.15					159	0.59	1%	48.15
<i>Hordeum vulgare</i> (rachis)	8	0.04	0%	15.38					22	0.08	0%	18.52
<i>Hordeum vulgare</i> (fragments)	1	0.01	0%	7.69					2	0.01	0%	7.41
cf. immature or wild <i>Hordeum</i>	1	0.01	0%	7.69					1	0.00	0%	3.70
<i>Triticum aestivum/turgidum</i>	29	0.15	1%	61.54					78	0.29	1%	59.26
<i>Triticum aestivum</i> (rachis)	38	0.20	1%	7.69					38	0.14	0%	11.11
<i>Triticum aestivum/turgidum</i> (fragments)	1	0.01	0%	23.08					1	0.00	0%	3.70
<i>Triticum</i> sp. (rachis)	1	0.01	0%	7.69					1	0.00	0%	3.70
<i>Panicum miliaceum</i>	21	0.11	0%	53.85	179	44.75	12%	100	279	1.03	2%	51.85
<i>Panicum miliaceum</i> (fragments)	1	0.01	0%	7.69					3	0.01	0%	7.41
<i>Setaria italica</i>	19	0.10	0%	38.46	50	12.50	3%	100	122	0.45	1%	48.15
<i>Setaria italica</i> (fragments)	1	0.01	0%	7.69					1	0.00	0%	3.70
indeterminate millet grain	33	0.17	1%	46.15	87	21.75	6%	100	216	0.80	2%	62.96
<i>Cerealia</i>	6	0.03	0%	23.08					19	0.07	0%	29.63
<i>Cerealia</i> (fragments)	113	0.59	2%	76.92	4	1.00	0%	100	447	1.66	3%	77.78
culm or node	115	0.60	2%	76.92	76	19.00	5%	100	221	0.82	2%	70.37
palea/lemma	279	1.45	5%	23.08					283	1.05	2%	18.52
Spikelet Fork	20	0.10	0%	30.77					33	0.12	0%	29.63
Awn	15	0.08	0%	15.38					162	0.60	1%	18.52
Fabaceae												
<i>Pisum sativum</i>	6	0.03	0%	15.38					23	0.09	0%	18.52
cf. <i>Pisum</i>									1	0.06	0%	3.70
cf. <i>Pisum</i> (fragments)									6	0.02	0%	7.41

Table 5. Continued (page 2 of 4)

Domesticated Totals:		304	1.58	6%	320	80.00	22%			1366	5.06	10%
Total Cereals (seeds + fragments)		304	1.58	6%	320	80.00	22%			1366	5.06	10%
Total Legumes (seeds + fragments)		6	0.03	0%	0	0.00				30	0.11	0%
Total Domesticates (Cereals + Legumes)		310	1.61	6%	320	80.00	22%			1396	5.17	10%
Total processing byproducts		476	2.48	9%	76	19.00	5%			760	2.81	6%
Wild												
Alliaceae												
<i>Alium</i> sp.										3	0.01	0%
Asteraceae												
<i>Artemisia</i> sp.		43	0.22	1%						205	0.76	2%
Asteraceae sp.										1	0.00	0%
Amaranthaceae					1	0.25	0%	100				
<i>Cheno-ams</i>		284	1.48	5%						689	2.55	5%
<i>Chenopodium</i> spp.		921	4.80	18%	94	23.50	6%	100	15.00	2574	9.53	19%
<i>Amaranthus</i> sp.		7	0.04	0%						81	0.30	1%
Brassicaceae												
<i>Thlapsi arvense</i>		2	0.01	0%	1	0.25	0%	100		4	0.01	0%
Caryophyllaceae												
<i>Saponaria</i>		1	0.01	0%						1	0.00	0%
<i>Vaccaria/Saponaria</i>		144	0.75	3%						409	1.51	3%
Caryophyllaceae spp.		8	0.04	0%	2	0.50	0%	100		21	0.08	0%
Cyperaceae												
Cyperaceae spp.		161	0.84	3%	2	0.50	0%	100	1.00	305	1.13	2%
<i>Carex</i> spp.		139	0.72	3%	2	0.50	0%	100	0.12	428	1.59	3%
Poaceae												
cf. <i>bromus</i>										1	0.00	0%
cf. <i>digitaria</i>		72	0.38	1%	101	25.25	7%	100		187	0.69	1%
<i>Panicoid</i> -Type		38	0.20	1%	21	5.25	1%	100		164	0.61	1%
Poaceae spp.		33	0.17	1%						8	0.03	0%
<i>Pooid</i> -Type		4	0.02	0%	7	1.75	0%	100		33	0.12	0%
<i>Setaria</i> (cf. <i>viridis</i>)		8	0.04	0%	9	2.25	1%	100		45	0.17	0%
small millet with chaff		21	0.11	0%						21	0.08	0%

Table 5. Continued (page 3 of 4)

<i>Stipa</i> -Type	33	0.17	1%	53.85	23	5.75	2%	100		128	0.47	1%	59.26			
Fabaceae																
cf. <i>Astragalus</i>										1	0.00	0%	3.70			
cf. <i>Medicago/Trifolium/Mellilotus</i>	1075	5.60	21%	84.62					9.00	1.06	31%	100	1561	5.78	11%	88.89
Fabaceae spp.	5	0.03	0%	23.08	6	1.50	0%	100					13	0.05	0%	22.22
<i>Trifolium</i>													2	0.01	0%	3.70
<i>Trigonella</i> -Type													2	0.01	0%	7.41
<i>Vicia</i> sp.	3	0.02	0%	15.38									4	0.01	0%	11.11
<i>Galega</i> sp.	16	0.08	0%	15.38									16	0.06	0%	7.41
Juncaceae																
Juncaceae sp.	1	0.01	0%	7.69									1	0.00	0%	3.70
Malvaceae																
<i>Malva</i> (cf. <i>sylvestris</i>)	1	0.01	0%	7.69									2	0.01	0%	7.41
Plantaginaceae																
<i>Plantago</i> sp.													1	0.00	0%	3.70
Polygonaceae																
Polygonaceae spp.	8	0.04	0%	15.38									87	0.32	1%	18.52
<i>Polygonum</i> (<i>persicaria</i> -Type)													19	0.07	0%	14.81
<i>Polygonum</i> spp.	81	0.42	2%	61.54									130	0.48	1%	51.85
<i>Rumex</i>	10	0.05	0%	23.08									28	0.10	0%	40.74
Rosaceae																
<i>Fragaria/Potentilla</i>	45	0.23	1%	69.23	11	2.75	1%	100					253	0.94	2%	66.67
Rubiaceae																
<i>Galium</i> sp.	75	0.39	1%	61.54					1.00	0.12	3%	100	90	0.33	1%	55.56
Solanaceae																
<i>Hyoscyamus niger</i>	9	0.05	0%	30.77					3.00	0.35	10%	100	18	0.07	0%	33.33
Solanaceae spp.													4	0.01	0%	3.70
Verbenaceae																
<i>Veronica</i>	7	0.04	0%	23.08									9	0.03	0%	14.81
Violaceae																
Violaceae spp.	2	0.01	0%	7.69									2	0.01	0%	3.70

Table 5. Continued (page 4 of 4)

Collated results from 2011 and 2023 excavations

The 2023 macrobotanical remains substantially increases the paleoethnobotanical record at Tasbas and broadens our understanding, both compositionally and diachronically, of human-plant interactions at the site. The contexts dated to the MBA (1951 – 1775 cal. BCE) provides new information regarding incipient domestic plant use at Tasbas. In particular, the broomcorn millet (and to a lesser extent foxtail millet) grains recovered increases more than ten-fold the millet presence in the early 3rd - 2nd millennium BCE. The 2023 samples also expand the data for the FBA and Iron Ages, presenting a maintenance of the agricultural system that was established in the MBA and continued into at least the EIA, with diachronic changes in the dominant cereals. The unique LIA assemblage from the Wusun burial shows a different depositional context and highlights the symbolic or economic importance of broomcorn and foxtail millets to this pastoralist community. The wild assemblage compliment those from the 2011 excavations and similarly show the likely remains of both dung burning (and thus animal forage practices) and the broader cultivation system, which is further explored in the Discussion.

To gain a grounded understanding of macrobotanical remains at Tasbas, I combined the results from the 2023 excavations and 2011 excavations analyzed by Robert Spengler for his dissertation (Spengler, 2013 Appendix F, Table 3) and presented in related publications (Spengler, 2013; Spengler et al., 2014b; Doumani et al., 2015). The densities of the identifiable domesticated assemblage (seeds and seed fragments) from the Middle Bronze Age to the Early Iron Age are displayed in Figure 10. I calculated densities per seed count / liters floated per time period (for 4 samples from the 2011 season, liters were unreported, so I used a calculated average liter floated of 6.28). I calculated ubiquities using the total contexts a taxon was present / total contexts per time period. As the macrobotanicals from the EBA and LIA are primarily from

unique burial contexts, I excluded them from the main Figure 10 and included them in Supplementary Figure 8 and discuss them below. Table 6 presents the count (n), density (ρ), ubiquity (u) and proportion (%) of domestic assemblage of identifiable domestic seeds through all time periods. Unidentifiable *Cerealia* (likely either wheat or barley) and indeterminate millet grains were not included in these calculations. The domestic assemblage in the EBA has a small number of domestic grains ($n = 8$) from a burial cist context and is composed primarily of 5 free-threshing wheat ($\rho = 0.15$, 63 %), 2 broomcorn millet ($\rho = 0.06$, 25 %) and 1 foxtail millet (0.03 density, 13 %). During the MBA, barley (likely all of the naked variety) were introduced. Broomcorn millet ($\rho = 2.52$, 62%) dominated the assemblage, followed by free-threshing wheat (0.8 density, 14 %), with a few barley and foxtail millet. During the LBA and FBA, the dominate domesticated taxa switched to barley (again, likely naked) ($\rho = 7.09$, 72 % and $\rho = 2.14$, 74 %, respectively), with all other identified domesticates at or below 1.08 density and 17 %. In the EIA, the domesticate proportions are more evenly dispersed, with 34% barley (likely both naked and hulled) ($\rho = 0.21$), 25 % free-threshing wheat ($\rho = 0.16$), 18 % broomcorn millet ($\rho = 18$ %), 17 % foxtail millet ($\rho = 0.1$), and 5 % green pea ($\rho = 0.03$). The LIA samples (from the unique burial context associated with the Wusun excavated in 2023 and an ashy fill deposited excavated in 2011) are dominated by broomcorn millet ($\rho = 18.77$, 75 %) and foxtail millet ($\rho = 5.19$, 14 %), with some naked barley ($\rho = 1.04$, 3 %). The evidence for local crop processing, and thus local cultivation, first appears in the LBA and continues into the IA. This is displayed in a heatmap (Figure 11) and Table 7, which presents the proportion of the identifiable domesticated cereal assemblage of free-threshing wheat, barley, broomcorn and foxtail millet, and processing by-products, from the EBA to LIA. Barley rachises first appear in the LBA and bread wheat rachises appear in the EIA assemblage from the *tandyr* oven context. The culms and nodes from

the LIA period are likely remnants of the charred plant textile mat that the individual was interred on and might be those of broomcorn and foxtail millet, but further work is needed to confirm this identification. Overall, there are changes diachronically at Tasbas, even when removing the very unique ritual/burial taphonomic contexts that represent the EBA and some of the LIA samples. Further, much of the domestic assemblage from the EIA were recovered from a *tandyr* oven feature, which likely enhanced preservation of the delicate by-product remains. It is likely both taphonomic characteristics and changes in subsistence activities driving the diachronic trends at Tasbas.

Table 6. Results of analysis of 2011 and 2023 identifiable domesticates (seeds and fragments) by count (n), density (ρ), proportion (%) and ubiquity (u). Densities were calculated by seed count per total liters floated per time period; proportions were calculated based on total number of seeds in identifiable domestic assemblage per time period; and ubiquities were calculated by total contexts a taxon was present / total contexts per time period.

Period	Total contexts	Total seeds	statistic	<i>Hordeum vulgare</i>	<i>Triticum aestivum/ turgidum</i>	<i>Panicum miliaceum</i>	<i>Setaria italica</i>	<i>Pisum sativum</i>	
EBA	3	8	<i>n</i>			5	2	1	
			<i>ρ</i>			0.15	0.06	0.03	
			%			63%	25%	13%	
			<i>u</i>			66.67	33.33	33.33	
MBA	2	68	<i>n</i>		1	13	41	8	
			<i>ρ</i>		0.06	0.80	2.52	0.49	
			%		2%	21%	65	13%	
			<i>u</i>		50	100	100	100	
LBA	13	656	<i>n</i>		472	20	46	45	73
			<i>ρ</i>		7.09	0.31	0.68	0.70	1.08
			%		72%	3%	7%	7%	11%
			<i>u</i>		53.85	46.15	38.46	38.46	30.77
FBA	4	123	<i>n</i>		83	19	14	5	2
			<i>ρ</i>		2.14	0.51	0.39	0.08	0.06
			%		67%	15%	11%	4%	2%
			<i>u</i>		75	50	75	25	25
EIA	12	119	<i>n</i>		41	30	22	20	6
			<i>ρ</i>		0.21	0.16	0.11	0.10	0.03
			%		34%	25%	18%	17%	5%
			<i>u</i>		50	66.67	58.33	41.67	16.67
LIA	2	265	<i>n</i>		11		199	55	
			<i>ρ</i>		1.04		18.77	5.19	
			%		4%		75%	21%	
			<i>u</i>		50		100	100	

Table 7. Results of analysis of identifiable domesticates (seeds and fragments) and crop processing by-products by count (*n*) and proportion (%) of assemblage.

	EBA		MBA		LBA		FBA		EIA		LIA		All time	
Total count:	8		63		695		301		589		341		1997	
	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%
<i>Hordeum vulgare</i>			1	2%	472	68%	83	28%	41	7%	11	3%	608	30%
<i>Hordeum</i> (rachis)					1		13	4%	8	1%			22	1%
<i>Triticum aestivum/turgidum</i>	5	63%	13	21%	21	3%	18	6%	30	5%			87	4%
<i>Triticum aestivum</i> (rachis)									38	6%			38	2%
<i>Triticum</i> sp. (rachis)									1	0%			1	0%
<i>Panicum miliaceum</i>	2	25%	41	65%	46	7%	14	5%	22	4%	199	58%	324	16%
<i>Setaria italica</i>	1	13%	8	13%	45	6%	5	2%	20	3%	55	16%	134	7%
culm or node					15	2%	15	5%	115	20%	76	22%	221	11%
Awn					16	2%	144	48%	15	3%			175	9%
palea/lemma					4	1%			279	47%			283	14%
Spikelet Fork/Rachis					75	11%	9	3%	20	3%			104	5%

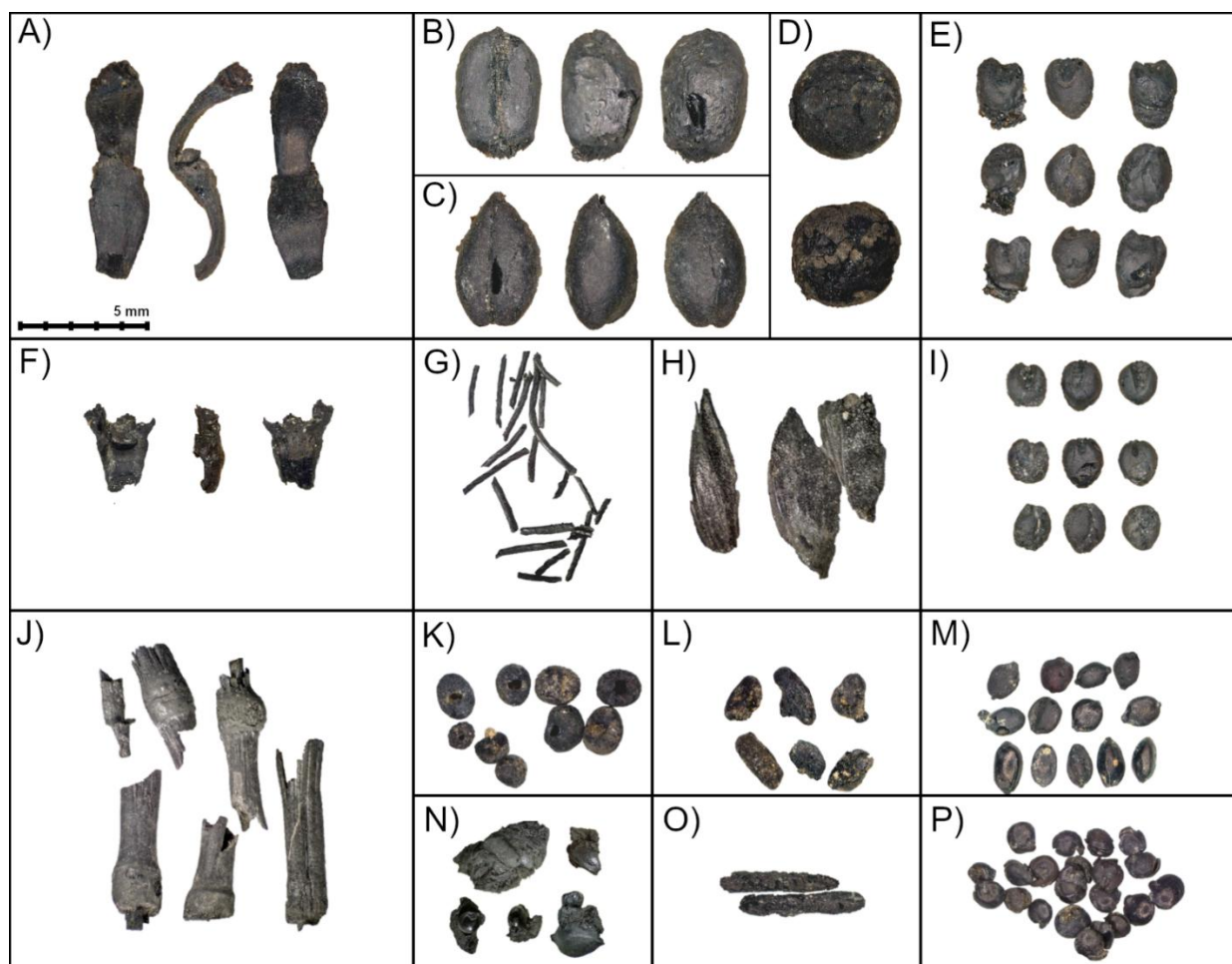


Figure 9. Selection of macrobotanical remains from the 2023 excavation: A) bread wheat rachis segment; B) ventral, lateral, and dorsal view of wheat grain with preserved hairs; C) ventral, lateral, and dorsal view of naked barley grain; D) pea seed with hilum present (top); E) from top to bottom: dorsal, lateral, and ventral view of broomcorn millets; F) barley rachis; G) awns; H) palea/lemma; I) from top to bottom, dorsal, lateral and ventral view of foxtail millets; J) culm nodes; K) *Galium* spp.; L) *Medicago/Trigonella/Melilotus*; M) *Carex* spp.; N) wild seeds in dung; O) *Stipa* sp.; P) *Chenopodium album*.

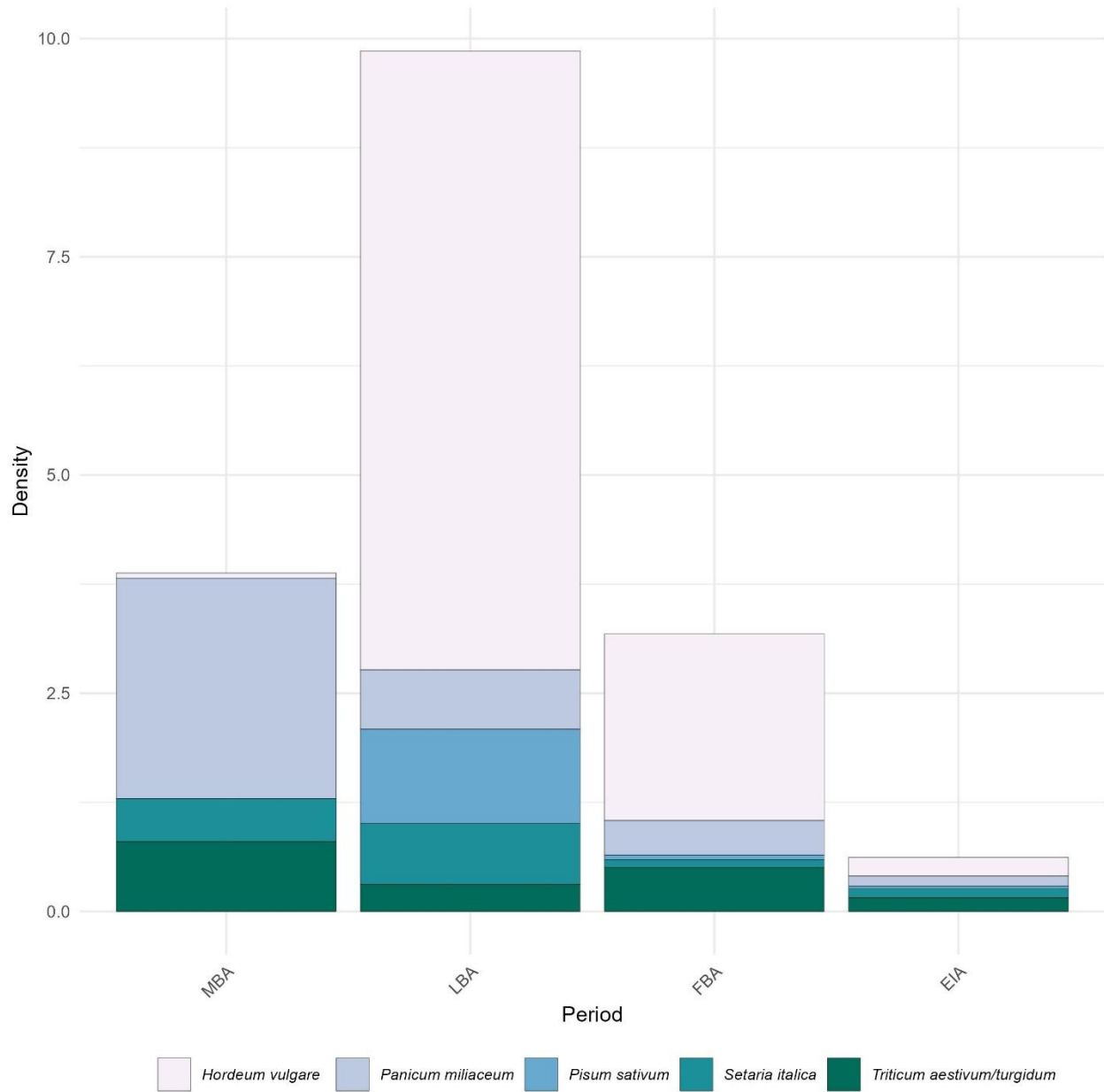


Figure 10. Stacked bar charts displaying change in densities of identified domesticated taxa through time (Middle Bronze Age to Early Iron Age) recovered from 2011 and 2023 excavations.



Figure 11. Heatmap displaying the proportion of the domesticated cereal assemblage of free-threshing wheat, barley, and crop-processing byproducts: rachises, awns, indeterminate Spikelet Fork/Rachis, and culms or nodes from both the 2011 and 2023 datasets. Data is located in Table 7.

3.3.2 Stable isotope results

Domesticated crops

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ results of all domesticated grains are summarized in Table 8, and fully reported in Supplementary Table 13. Figure 12 presents the isotopic values of free-threshing wheat and barley, while Figure 13 presents the isotopic values of peas. $\delta^{13}\text{C}$ of free-threshing wheat ranges from 15.6 ‰ to 19.5 ‰, $M = 17.4$ ‰ [17.0, 17.8], $n = 24$, and of barley from 13.2 ‰ to 23.7 ‰, $M = 17.6$ ‰ [17.2, 18.0], $n = 71$. $\delta^{15}\text{N}$ of free-threshing wheat ranges from 2.1 ‰ to 13.0 ‰, $M = 4.7$ ‰ [3.6, 5.89] and of barley from 1.3 ‰ to 11.8 ‰, $M = 6.4$ ‰ [5.9, 7.0]. The majority of free-threshing wheat have $\delta^{13}\text{C}$ values above the superfluous watering threshold and barley above the optimal watering threshold. The majority of both free-threshing wheat and barley have $\delta^{15}\text{N}$ values above the natural vegetation baselevel.

To investigate further the diachronic changes in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of barley and wheat, I analyzed the differences in CIs of the means between each time period (Figure 12, Supplementary Figure 9, Supplementary Table 14). Here, I present a few interesting trends. Overall, barley $\delta^{13}\text{C}$ values are relatively similar through time, with a slight increase in mean values from the LBA 17.1 ‰, $n = 44$, to the FBA 18.5 ‰, $n = 15$, with a mean difference of 1.4 ‰ [0.6, 2.2]. This suggests that the mean difference between the $\delta^{13}\text{C}$ values of LBA and FBA barley is plausibly anywhere between 0.6 and 2.2 ‰. There is no overlap in the CIs of the two groups, with suggests that this is a notable difference. There is a slight decrease in mean $\delta^{13}\text{C}$ values of barley from the EIA 18.7 ‰, $n = 15$, to the LIA 17.3 ‰, $n = 8$, with a mean difference of -1.4 ‰ [-4.3, 1.5]. This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{13}\text{C}$ values of EIA and LIA barley is plausibly anywhere between -4.3 and 1.5 ‰. There is substantial overlap in CIs, with suggests this is not a notable difference.

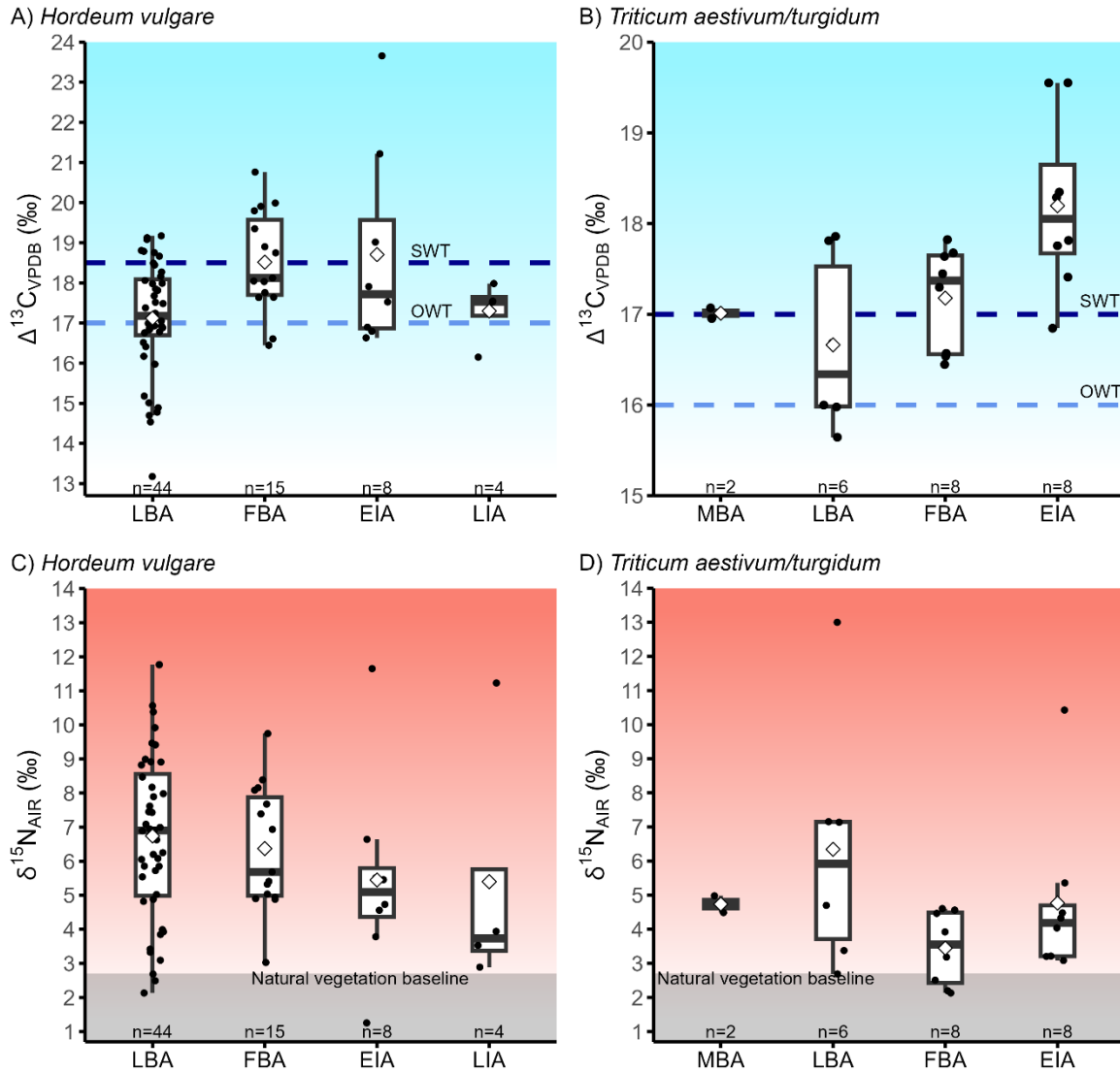


Figure 12. Boxplots presenting the results of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analyses of free-threshing wheat (C and D) and barley (A and B). Diamonds represent the calculated means. Dashed blue horizontal lines in $\Delta^{13}\text{C}$ plots represent the Superfluous Watering Threshold (SWT) and Optimal Watering Threshold (OWT) for each respective taxon. The shaded gray area in the $\delta^{15}\text{N}$ plots represents the calculated natural vegetation baselevel.

Regarding the $\delta^{15}\text{N}$ values of barley, there is a general decrease in $\delta^{15}\text{N}$ values through all time periods. $\delta^{15}\text{N}$ values decrease from the LBA, 6.7‰, $n = 44$, to FBA, 6.4 ‰, $n = 15$, with a mean difference of -0.4 ‰ [-0.4, -1.8]. This suggests that the mean difference between the $\delta^{15}\text{N}$ values of LBA and FBA barley is plausibly anywhere between -0.4 and -1.4 ‰. There is substantial overlap in the CIs, which suggests this is not a notable difference in means. There is a decrease in mean $\delta^{15}\text{N}$ values from the FBA, 6.4 ‰, $n = 15$, to the EIA, 5.4 ‰, $n = 8$, with a mean difference of -0.9 ‰ [-3.0 1.1]. This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{15}\text{N}$ values of FBA and EIA barley is plausibly anywhere between -3.0 to 1.1 ‰. There is substantial overlap in CIs, which suggests this is not a notable difference in means.

For free-threshing wheat, there is an overall increase in $\delta^{13}\text{C}$ values through time starting from the LBA, with a variable $\delta^{15}\text{N}$ values (Figure 12, Supplementary Figure 10, Supplementary Table 14). There is an increase in mean $\delta^{13}\text{C}$ values from the LBA 16.7 ‰, $n = 7$, to the FBA 17.2 ‰, $n = 8$, with a mean difference of 0.5 ‰ [-0.4, 1.4]. This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{13}\text{C}$ values of LBA and FBA free-threshing wheat is plausibly anywhere between -0.4 and 1.4 ‰. There is considerable overlap in the CIs, which indicates this is not a notable difference. There is an increase in mean $\delta^{13}\text{C}$ values from the FBA, 17.2 ‰, $n = 8$, to the EIA, 18.2 ‰, $n = 8$, with a mean difference of 1.0 ‰ [0.2, 1.9]. This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{13}\text{C}$ values of FBA and EIA free-threshing wheat is plausibly anywhere between 0.2 and 1.9 ‰. There is slight overlap in the CIs, which suggests this might be a notable difference.

There is a decrease in the mean free-threshing wheat $\delta^{15}\text{N}$ values from the LBA 6.3 ‰, n = 6, to the FBA 3.5 ‰, n = 8, with a mean difference of -2.9 ‰ [-5.9, 0.1]. This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{15}\text{N}$ values of LBA and FBA free-threshing wheat is plausibly anywhere between -5.9 and 0.1‰. There is considerable overlap in the CIs, which suggests this is not a notable difference. There is an increase in mean $\delta^{15}\text{N}$ values from the FBA, 3.5 ‰, n = 8, to the EIA, 4.8 ‰, n = 8, with a mean difference of 1.3 ‰ [-0.7, 3.3]. This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{15}\text{N}$ values of FBA and IA free-threshing wheat is plausibly anywhere between -0.7 and 3.3 ‰. There is considerable overlap in the CIs, which suggests this is not a notable difference.

The 11 pea seeds analyzed come from a Late Bronze Age layer (Figure 13). The $\delta^{13}\text{C}$ values of the peas range from 16.6 to 19.1 ‰ and the $\delta^{15}\text{N}$ range from 1.0 to 3.9 ‰. Only one $\delta^{13}\text{C}$ value falls below the SWT. The mean $\delta^{13}\text{C}$ value of all peas is 17.9 ‰ [17.4, 18.3] which is above the SWT. The peas have a mean $\delta^{15}\text{N}$ value of 2.1 ‰ [1.5, 2.7], which is below the natural vegetation baselevel. This is due to peas being nitrogen fixing plants which are less impacted by soil ^{15}N enrichment than cereal crops as their primary source of nitrogen is from the atmosphere, which is 0 ‰ (Fraser et al., 2011; Vaiglova et al., 2014a). Non-manured pulses have $\delta^{15}\text{N}$ values below 0‰ (Fraser et al., 2011). All the pea $\delta^{15}\text{N}$ values analyzed are above 0‰.

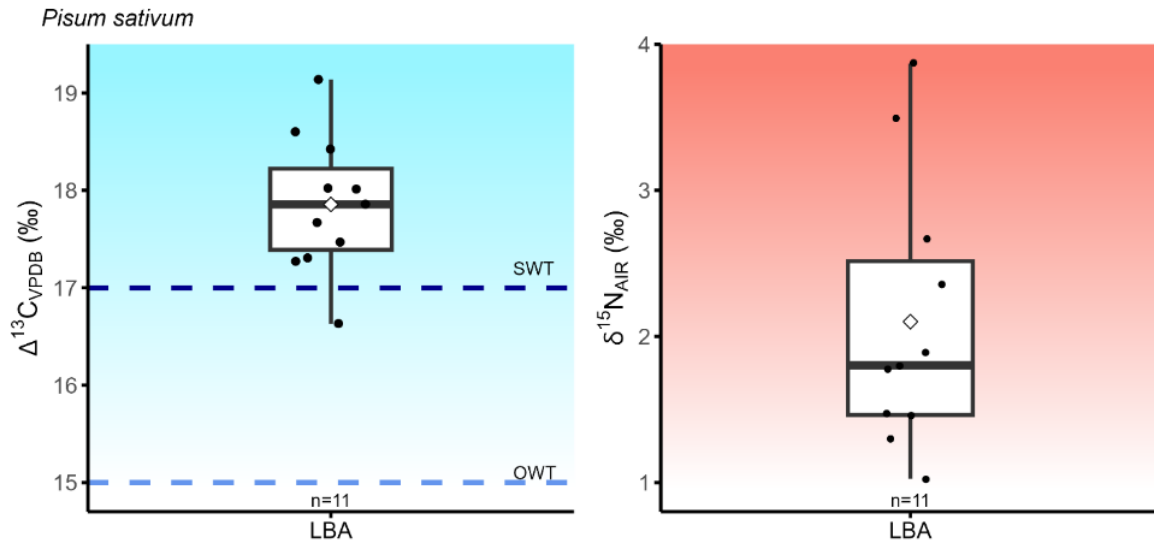


Figure 13. Boxplots presenting the $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of green peas. Diamonds represent calculated means. Dashed blue horizontal lines in $\Delta^{13}\text{C}$ represent the Superfluous Watering Threshold (SWT) and Optimal Watering Threshold (OWT) for peas. The shaded gray area represents in the $\delta^{15}\text{N}$ plot represents the calculated natural vegetation baselevel.

Table 8. $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ results of free-threshing wheat, barley, and green peas.

			$\Delta^{13}\text{C}$			$\delta^{15}\text{N}$		
Time Period	Taxa	N	mean $\pm$ SD (1 σ) (‰)	95 CI [LL, UL]	median	mean $\pm$ SD (1 σ) (‰)	95 CI [LL, UL]	median
All Periods combined	<i>Triticum aestivum/turgidum</i>	24	17.4 $\pm$ 1.0	[17.0, 17.8]	17.4	4.7 $\pm$ 2.5	[3.7, 5.8]	4.4
	<i>Hordeum vulgare</i> (naked)	71	17.6 $\pm$ 1.6	[17.2, 18]	17.5	6.4 $\pm$ 2.5	[5.9, 7.0]	6.2
	<i>Pisum sativum</i>	11	17.9 $\pm$ 0.7	[17.4, 18.3]	17.9	2.1 $\pm$ 0.9	[1.5, 2.7]	1.8
MBA 1950 - 1775 BCE	<i>Triticum aestivum/turgidum</i>	2	17.0 $\pm$ 0.1	[16.3, 17.8]	17	4.7 $\pm$ 0.3	[1.6, 7.9]	4.7
LBA 1400 - 1200 BCE	<i>Triticum aestivum/turgidum</i>	6	15.8 $\pm$ 0.3	[13.7, 17.9]	15.8	6.3 $\pm$ 3.8	[2.4, 10.3]	5.9
	<i>Hordeum vulgare</i>	44	17.1 $\pm$ 1.4	[16.7, 17.5]	17.2	6.7 $\pm$ 2.5	[6.0, 7.5]	6.9
	<i>Pisum sativum</i>	11	17.9 $\pm$ 0.7	[17.4, 18.3]	17.9	2.1 $\pm$ 0.9	[1.5, 2.7]	1.8
FBA 1200 - 1000 BCE	<i>Triticum aestivum/turgidum</i>	8	17.2 $\pm$ 0.6	[16.7, 17.7]	17.4	3.5 $\pm$ 1.1	[2.5, 4.3]	3.6
	<i>Hordeum vulgare</i>	15	18.5 $\pm$ 1.3	[17.8, 19.2]	18.1	6.4 $\pm$ 1.8	[5.4, 7.4]	5.7
EIA 1000 - 500 BCE	<i>Triticum aestivum</i>	8	18.2 $\pm$ 1.0	[17.4, 19.0]	18.1	4.8 $\pm$ 2.4	[2.7, 6.8]	4.2
	<i>Hordeum vulgare</i>	8	18.7 $\pm$ 2.51	[16.6, 20.8]	17.7	5.5 $\pm$ 3.0	[3.0, 7.9]	5.1
LIA 126 - 304 CE	<i>Hordeum vulgare</i>	4	17.3 $\pm$ 0.8	[16.0, 18.6]	17.5	5.4 $\pm$ 3.9	[-0.8, 11.6]	3.7

Wild Taxa

To further characterize the surrounding environment and growing conditions at Tasbas, I analyzed the $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of well represented wild taxa in the macrobotanical assemblage. These are also common weedy species of arable landscapes. Figure 14 presents boxplots of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of *Chenopodium album*, *Galium* sp., *Stipa*, wild Fabaceae (*Medicago*, *Trigonella*, *Trifolium*, *Melilotus*), and tentatively identified wild *Hordeum*. Each point represents a homogenized sample. Due to the small sample size, I am limited to descriptive

statistics of these results. The $\delta^{13}\text{C}$ values of *Chenopodium album* range from 13.1 to 21.2 ‰, mean = 18.7 ‰ [16.0, 21.4], n = 7, *Galium* sp. from 17.9 to 20.2 ‰, mean = 18.9 ‰ [17.9, 20.0], n = 5, *Stipa* sp. from 15.4 to 16.4 ‰, mean = 15.9 ‰ [9.7, 22.1], n = 2, and the wild Fabaceae from 16.2 to 18.0 ‰, mean = 17.0 [16.4, 17.5], n = 7. The one cf. wild *Hordeum* grain $\delta^{13}\text{C}$ analysis failed to produce a reliable value. The $\delta^{15}\text{N}$ values of *Chenopodium album* range from 9.1 to 12.0 ‰, mean = 10.4 ‰ [9.5, 11.4], *Galium* sp. from 4.0 to 9.9 ‰, mean = 5.7 ‰ [1.3, 10.2], *Stipa* sp. from 6.5 to 6.9 ‰, mean = 6.7 ‰ [4.1, 9.3], and the wild Fabaceae from 1.9 to 3.9 ‰, mean = 3.2 ‰ [2.5, 3.9]. The one cf. wild *Hordeum* has a $\delta^{15}\text{N}$ value of 10.0 ‰.

There are chronological differences in the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the wild taxa. The sample size limits statistical analyses, so I provide simple descriptions of these changes. There is a decrease in $\delta^{13}\text{C}$ values of *Chenopodium album* through time coupled with an increase in $\delta^{15}\text{N}$ values. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of *Galium* sp. decrease from the LBA to EI. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wild Fabaceae increase from the LBA to FBA and then decrease through the Iron Ages.

Table 9. $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wild taxa: *Chenopodium album*, *Galium* sp., *Stipa* sp., wild Fabaceae, and cf. wild Hordeum.

Time Period	Taxa	N	$\Delta^{13}\text{C}$			$\delta^{15}\text{N}$		
			mean $\pm$ SD (1 σ) (‰)	95 CI [LL, UL]	median	mean $\pm$ SD (1 σ) (‰)	95 CI [LL, UL]	median
All Periods	<i>Chenopodium album</i>	7	18.7 $\pm$ 2.9	[16.0, 21.4]	20.1	10.4 $\pm$ 1.0	[9.5, 11.4]	10.6
	<i>Galium</i> sp.	4	19.0 $\pm$ 1.0	[17.4, 20.5]	18.9	6.1 $\pm$ 3.3	[-2.0, 14.3]	4.5
	<i>Stipa</i> sp.	2	15.9 $\pm$ 0.7	[9.7, 22.1]	15.9	6.7 $\pm$ 0.3	[4.1, 9.3]	6.73
	wild Fabaceae	7	17.0 $\pm$ 0.6	[16.4, 17.5]	17.1	3.2 $\pm$ 0.7	[2.5, 3.9]	3.5
	wild Hordeum	1				10.0		
LBA 1065 -825 BCE	<i>Chenopodium album</i>	5	18.4 $\pm$ 3.5	[14.1, 22.7]	20.1	10.1 $\pm$ 0.9	[9.0, 11.2]	9.8
	<i>Galium</i> sp.	2	19.6 $\pm$ 0.9	[12.0, 27.2]	19.6	7.0 $\pm$ 4.2	[-30.7, 44.6]	7
	<i>Stipa</i> sp.	2	15.9 $\pm$ 0.7	[9.7, 22.1]	15.9	6.7 $\pm$ 0.3	[4.1, 9.3]	6.7
	wild Fabaceae	4	16.8 $\pm$ 0.5	[16.1, 17.5]	16.9	3.5 $\pm$ 0.3	[3.1, 3.9]	3.6
	wild Hordeum	1				10.0		
FBA 1065 -825 BCE	<i>Chenopodium album</i>	1	20.4			10.6		
	wild Fabaceae	1	18.0			3.9		
EIA 1000 - 500 BCE	<i>Galium</i> sp.	2	18.3 $\pm$ 0.7	[12.2, 24.5]	18.3	4.5		
	wild Fabaceae	1	17.2			2.5		
LIA 126 - 304 CE	<i>Chenopodium album</i>	1	19.0			12		
	wild Fabaceae	1	16.4			1.9		

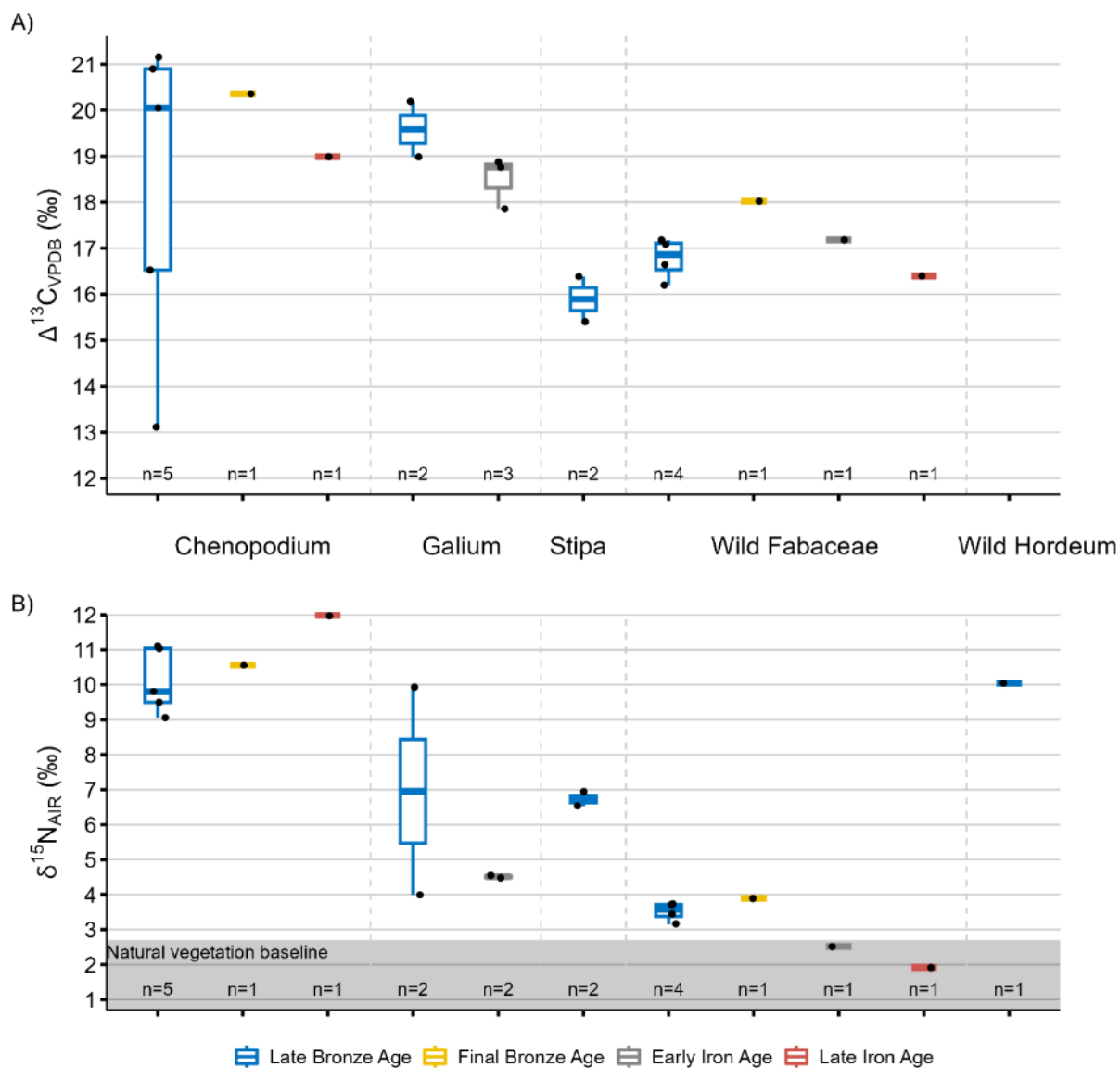


Figure 14. Boxplots presenting the $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wild taxa from Late Bronze Age, Final Bronze Age, and Iron Age deposits.

3.4 Discussion

The results of the macrobotanical and stable isotope analysis present a dynamic agricultural system at Tasbas, that incorporated numerous domesticated crops that require different approaches to cultivation. The results of the plant stable isotope analyses provide data to investigate ancient labor strategies in the form of water and soil management.

3.4.1 Cultivation complexity at Tasbas

Macrobotanical results reveal a complex agricultural system utilized by inhabitants of Tasbas over the course of more than two millennia. The free-threshing wheat from the EBA, as discussed previously (Doumani et al., 2015), are from a cremation cist context and resonates closely with a similar ritual context at the site of Begash in a neighboring valley (Frachetti et al., 2010). A few grains of broomcorn and foxtail millet were recovered from directly above this cist (Spengler et al. 2013), but it is unclear whether they are associated with the EBA or later layers. Initially interpreted as likely trade for ritual purposes, subsequent stable isotope analysis of domestic livestock from Tasbas, Begash and Dali, show livestock consumption of millet during this period (Hermes et al., 2019). The flora surrounding Tasbas was likely dominated by C_3 plants, based on carbon isotope values from the majority of herbivorous animals (Hermes et al., 2019). Thus, the presence of C_4 consumption in caprines and cattle from the EBA implies at least cultivation and foddering of millet for some of the livestock in the Bayan Zhurek Valley. Therefore, the presence of millets in the EBA is not surprising, as following research on millet impressions in ceramic assemblages from Tasbas, Dali, and Begash, and stable isotope analysis on material from Chap in Kyrgyzstan, provide evidence of millet presence and consumption by humans and animals as early as the EBA (Motuzaite-Matuzeviciute et al., 2022a; Endo et al.,

2023). By the MBA, we see the inception of a domestic crop complex at Tabas, which integrated free-threshing wheat, barley, and broomcorn and foxtail millet. The abundance of remains likely reflects local cultivation. In the LBA and Iron Age, there is clear evidence for local cultivation, in the ample presence of barley rachis, wheat rachis, and awn and chaff remnants. This is further supported by phytolith evidence for millet and wheat husks in LBA and IA layers from the 2011 excavation (Doumani et al., 2015). Disparate cultivation needs, sowing, and growth time of these domesticated crops would likely require multi-cropping or rotating fields.

Barley becomes the main domesticated crop in the Late Bronze to Iron Ages. Due to analysis time constraints, I was not able to thoroughly identify and count hulled and naked varieties of barley. I did notice that the Bronze Age samples lacked clear evidence of hulled barley grains that are present in the EIA samples (see Supplementary Figure 11 for an image of one of these hulled barleys from the *tandyr* oven). Presence of hulled barley grains in the Iron Age would align with finds from Tuzusai (Spengler et al., 2013a). Further work on these identifications will clarify the presence of these barley types. The cold-tolerance of naked barley grains likely contributed to its preferential cultivation in the Bronze Age samples (Knüpfper et al., 2003). Motuzaite Matuzeviciut et al. (2022b) also suggest that the naked barley found in the high-elevation site of Chap in Kyrgyzstan were also selected for its high yield in the highlands and ability to produce dark pigmented grains, which provides protection against UV radiation abundant at high elevations. Previously, identification of the wheat grains at Tasbas were limited to the category of “free-threshing wheat”, with two possibilities for species identification: *T. aestivum* or *T. turgidum*. (Spengler et al., 2014b). The wheat rachises recovered from the 2023 excavation are identifiable to *Triticum aestivum*, suggesting that the grains of free-threshing wheat from Tasbas are *Triticum aestivum* and not *Triticum turgidum*. The *T. aestivum* rachises

are found in the Tasbas Iron Age samples, so the identification of Early, Middle, and Late Bronze Age wheats at the site is presently unresolved. As a caveat, the majority of wheat found in Bronze and Iron Age Inner Asia and China are bread wheats, as attested by both morphological and genetic evidence, which supports the interpretation of the free-threshing wheats at Tasbas as *Triticum aestivum* (Li et al., 2011; Motuzaite-Matuzeviciute et al., 2022b).

3.4.2 Soil enrichment

The majority of $\delta^{15}\text{N}$ values of wheat and barley are above the estimated mean natural vegetation baselevel of 2.7 ‰. Additionally, when compared to manuring thresholds created by long-term agronomic experiments, most grains are above the low manuring threshold of 3 ‰ (Bogaard et al., 2013). Although other factors such as soil salinity and natural denitrification cannot be ruled out entirely, these results do suggest growing conditions in ^{15}N enriched plot relative to natural soil, most likely from the use of animal manure. Dung remains are found consistently in the macrobotanical samples, presumably used of fuel (as discussed at length by Spengler (2018), Miller and Smart (1984), and Miller and Marston (2012b), among others). Furthermore, the faunal remains of domestic livestock are found in all layers at Tasbas, which would provide abundant dung as a source of manure for fertilizer. Overall, there is a general decline in $\delta^{15}\text{N}$ values through time for barley grains (Figure 12). There is not as clear for wheat and is more variable over time. The average $\delta^{15}\text{N}$ values for barley and wheat in the LBA are above 6 ‰, which, according to Bogaard et al.'s (2013) experiments represent high manuring levels of more than 35 tons/hectare.

The peas from this period also have high $\delta^{15}\text{N}$ values, suggesting intensive manuring. For pulses, Fraser et al. (2011), in their study on experimentally grown and traditionally farmed cereals and pulses, record the highest $\delta^{15}\text{N}$ values of pulses, $M = 2.2 \text{ ‰} \pm 1.4$, were intensively

manured broad beans by traditional farmers in Evvia, Greece. Their experimentally grown peas had $\delta^{15}\text{N}$ values on average 0.3 ‰ higher than broad beans cultivated with similar manure applications. Low manure levels, ~ 15 -20 tons/hectare, for pulses did not result in any discernable changes in $\delta^{15}\text{N}$ values. It was only highly manured, intensive systems, such as those conducted by traditional farmers in Evvia, Greece, that resulted in discernable $\delta^{15}\text{N}$ values. This is due to fixation of atmospheric N_2 by legumes that results in generally low $\delta^{15}\text{N}$ values. Fraser conclude that only very intensive manuring of pulses, such as broad beans and peas, can be detected isotopically, while lower levels would not be. This research indicates that the high $\delta^{15}\text{N}$ values of the Tasbas peas are the result of intensive manuring of the plots.

During the Final Bronze and Iron Ages, these average values drop into the medium manuring threshold between 3 – 6 ‰, as defined by Bogaard et al. 2013. These trends could suggest increased extensification practices through time, leading to less labor input per area in the form of manure application for the barley and potentially wheat crops. Interpreted in this way, we may be seeing a transition from an earlier intensive garden-style cultivation, similar to forms found in Neolithic Central and Southeast Europe, to a more extensive cultivation system conducted with less labor input into cultivation (Bogaard, 2004). Similar trends leading to agricultural extensification has been observed in north China, including the eastern Tianshan during similar period (Tian et al., 2022). In this extensive system, allowing livestock to graze on the harvested or fallow fields, such as discussed by Halstead (2006) in some southern European agropastoral systems, without much additional manure application could contribute to these lower $\delta^{15}\text{N}$ signatures, but this has not been tested experimentally. This extensification trend presents more clearly for the barley data, while additional isotope analyses for wheat and peas across time periods would clarify trends.

3.4.3 Variable water-management at Tasbas

Turning to the possibility of water management, the high $\delta^{13}\text{C}$ values for the wheat grains and all the peas suggest that labor was dedicated to managing the water systems for these crops, whether that involved opportunistically planting crops in water-abundant areas (such as along streams or floodplain cultivation) or constructing simple irrigation or water-diverting systems, such as those used today by farmers in site area (Figure 15 B). The barley grains show less evidence of direct water management but still received optimal watering through most of the time periods studied. No physical evidence of archaeological irrigation systems, such as those found in the Kochkor Valley, Kyrgyzstan, near the site of Chap (Rouse and Krumnow, 2020; Rouse et al., 2022), have been identified near Tasbas, although as yet a systematic pedestrian and geophysical/spatial survey have not yielded evidence for such. Kuzmina (2008, pp. 74–77) posits that in the Late Bronze Age, organized by a central authority, irrigation in Central Asia was improved by communities transitioning from dammed channels to irrigated small fields and eventually to the construction of canals to irrigate fields up to one hectare in size. These labor-intensive farming systems were coupled with cattle, sheep/goat, and horse pastoralism.

In addition to the irrigation features near Chap, other evidence for early irrigation (4th-3rd mil. BC) is present across southern Central Asia at the sites of Geoksyur I and Jeitun (Lisitsina, 1969, 1981; Larkum, 2010). In the arid climate of southern Central Asia, particularly near the Kopet Dag foothills of Turkmenistan, irrigation was and continues to be essential for conducting plant cultivation of cereals and legumes (Lisitsina, 1969). Lisitsina (1981) argues that Bronze Age irrigation systems, which directed water from channeling water from rivers into irrigation fields with the use of *aryks* (irrigation canals) in the alluvial plains and *kjariz* (underground tunnels/wells that bring groundwater to surface) in the piedmont zones, allowed for intensive

irrigated agriculture and pastoralism driving surplus production, population, and proto-urban development. Additional evidence for Iron Age irrigation comes from irrigation canals in Tuva, Khemchik valley of Russia, associated with Kazylgan burials which include millet and grinding stones (Vainshtein, 1980, pp. 145–146). Similar to southern Central Asia, the vast arid steppe requires irrigation for plant cultivation and is ethnographically documented in many semi-nomadic communities (Vainshtein, 1980). Thus, irrigation was present in broader Central Asia during different periods in time, where arid ecologies necessitated intensive water-management. There remain questions, however, about the nature of water-management at Tasbas, where today two streams flow just meters from the site. These could have been diverted and/or dammed to obtain consistent water access through the summer growing season. Alternatively, the crops could have been planted near the streams or in naturally wetter environments, such as the grassy floodplain that is currently located between two arms of this stream (Figure 15). In southern Central Asia, Lisitsina (1981, p. 357) attests that “in the piedmont zone, it proved possible to cultivate low-yield dry-farming crops” and Dolukhanov (1981, p. 371) affirms that in modern times, dry farming in the Kopet Dagħ only is possible above 760 masl. During the Iron Age in Zhetysu, Wusun semi-nomadic communities practiced dryland agriculture in the foothills, utilizing mountain streams and simple irrigation systems and rainfall to water drought-tolerant millet and barley (Akishev, 1970). With rain-fed cultivation, risks of crop failure would be exacerbated and would require necessary supplements from other economic sectors, such as pastoralism or trade.

Today, the Bayan-Zhurek valley receives 200-500 mm average rainfall between April and October, primarily falling in March and April, with a sharp reduction in June and July. throughout the summer months. This rainfall and snowmelt affect the water levels in the streams.

Rainfall, like other ecological factors in Semirech'ye, vary greatly dependent on elevation, seasonality, and mountain rain shadow. In the lower-elevation steppe areas, rainfall does not typically surpass 200 mm/year, while in the mountain foothills, where Tasbas is situated, rainfall varies greatly and range between 450-800 mm/year (Utesheva, 1959). Climatic index calculations from phytoliths recovered at Tasbas indicated an increasing exploitation of warmer environments, with an increase in arid-adapted grasses from the Early Bronze to Late Bronze Age, followed by a cooler trend (Doumani et al., 2015). This may indicate a more arid climate in the Bronze Age than today, requiring water management to create the $\delta^{13}\text{C}$ results for wheat, barley, and peas. The $\delta^{13}\text{C}$ values of barley grains are below or within the OWT, which may imply rain-fed cultivation supplemented by some anthropogenic watering. The $\delta^{13}\text{C}$ values of wheat grains are within the OWT or above the SWT. The values above the SWT likely suggest deliberate watering, as the plant needs to be grown in overwhelmingly well-watered conditions to achieve such values. Additionally, the $\delta^{13}\text{C}$ values of the peas, all (but one) are above the SWT, which indicates purposeful water-management. Of all the crops present at Tasbas, peas require the most water for growth, nearly three times as much as the millets (Shantz and Piemeisel, 1927). This, coupled with the high pea $\delta^{15}\text{N}$ values, suggests a carefully managed system for peas, likely close to the settlement. In the foothills of Central Asia, "harnessing of water... is not particularly difficult and the mountain streams can easily be diverted to the fields" (Vainshtein, 1980, p. 145). Some management of water was likely practiced at Tasbas, as indicated by the $\delta^{13}\text{C}$ values and water-requirements of bread wheat and peas grown at the site, while barley may have been grown in a rain-fed, dryland system.

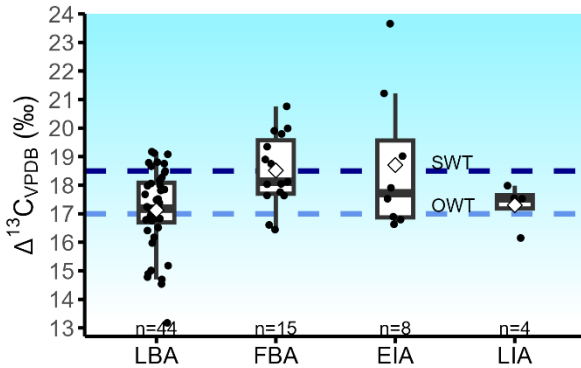
Looking further afield, when compared to archaeological isotope data of wheat and barley from regions that receive much higher rainfall, like Wales, UK, upwards of 3000

mm/year, the $\delta^{13}\text{C}$ values of Tasbas' wheat and barley further imply additional water-management. Treasure et al. (2019), in their study of Neolithic (4000-2000 BCE) wheat and barley remains from Wales, have $\delta^{13}\text{C}$ values above 17 ‰, with is the OWT for barley and the SWT for wheat. In this region that receives much higher rainfall per year than Tasbas, the $\delta^{13}\text{C}$ results are similar. This would imply that at least some of the water-availability for Tasbas grains came from anthropogenic sources. Otherwise, I would expect much lower $\delta^{13}\text{C}$ values.

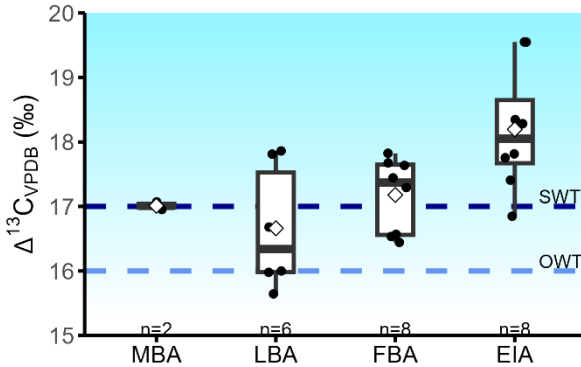


Figure 15. A) Photograph of the Tasbas (outlined in red box) and the adjacent seasonal streams and landform. Image taken facing west, atop a hill formation looking out over the valley and the Dzhungar Alatau to the south and west. Photo by Melissa M. Ritchey 2023. B) Photo of modern irrigation stream near Tasbas, location and direction of photo unknown. Photo by Natalie G. Mueller 2011.

A) *Hordeum vulgare*



B) *Triticum aestivum/turgidum*



C) Wild Taxa

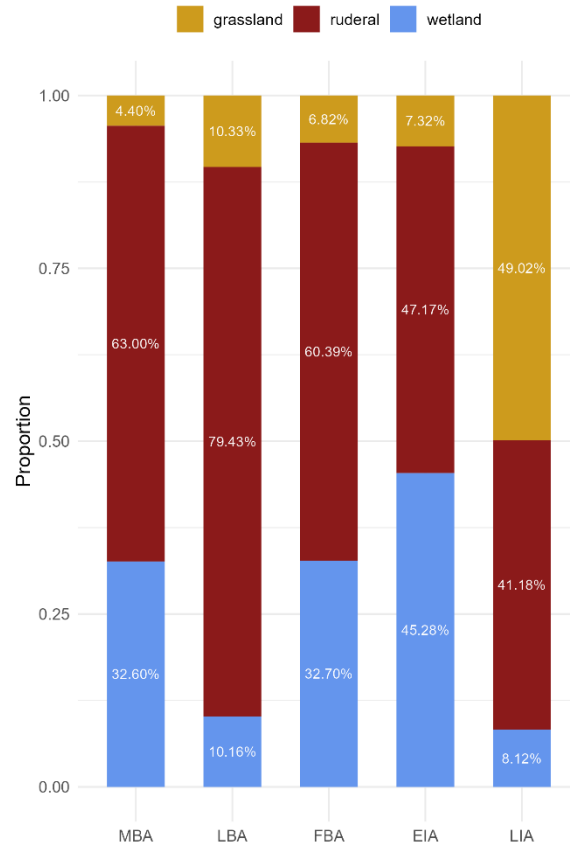


Figure 16. Figure comparing $\Delta^{13}\text{C}$ isotope results of A) barley and B) wheat, with C) the percentages of wild taxa habitats.

3.4.4 Weeds and crops

The stable isotope results and habitats of the wild taxa from Tasbas present a comparable dataset to inform our understanding of the cultivation system. As shown in Figure 14, the wild taxa $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values change through time. The wild Fabaceae, *Galium* sp., and *Chenopodium album* $\Delta^{13}\text{C}$ values follow trends seen in the barley grains but are opposite those seen in the wheat. This may further support the dryland cultivation of barley, with $\Delta^{13}\text{C}$ values reflecting mostly rainfall patterns with minor anthropogenic watering. The *Stipa*, a wild grass, is also below the OWT. The $\delta^{15}\text{N}$ values are more complex. *Chenopodium album* have a general increase in $\delta^{15}\text{N}$ values

through time, opposite the trend seen in domesticated taxa. This may suggest that the source of the *Chenopodium* is not from arable fields, but primarily from dung, and reflects an increase in overall ^{15}N around Tasbas from potential hotspots created by livestock, as seen in Southwest Kenyan grasslands (Marshall et al., 2018). Wild Fabaceae follow the general decrease in $\delta^{15}\text{N}$ values exhibited by the wheat and barley grains. The wild *Hordeum* (or immature grain) has a $\delta^{15}\text{N}$ above the natural baselevel, which suggests it was growing in a cultivated field. Analyzing the stable isotopes of wild taxa from archaeological sites is a new venture and future work clarifying the particular taxonomic fractionation processes and taphonomic sources will aid interpretations of these results.

As seen in the Chapter 2, comparing the percentages of wild taxa and the habitats they represent to the isotope results can help inform interpretations. Figure 16 presents this comparison for Tasbas, showing the changes in proportion of habitat type represented by wild taxa through time (Supplementary Table 15). The wetland habitat type, representing taxa that prefer water-abundant environments such as irrigation fields or near water sources, more closely matches the isotope results of wheat. There is a similar decrease in taxa representing wetland habitats from the MBA to LBA and a similar increase from the LBA to EIA. Conversely, the variation seen could also be driven by the taphonomic source of the wild taxa. Dung burning is apparent at Tasbas, with many of these wild seeds found in charred dung remnants from the macrobotanical samples (Figure 9 N). In addition to crop-processing, the source of many of these wild taxa could be coming from dung-burning. The changes in habitat composition are likely reflective of both these practices.

3.4.5 Tasbas in a regional context

Tasbas is one of many sites along the IAMC that integrated plant cultivation and animal husbandry during the Bronze and Iron Ages. Similar domesticated crop and livestock assemblages were recovered from the neighboring site of Begash, and other IAMC sites such as Chap I and II, Aigyrzhal-2, and the Tongtian Cave, (Frachetti et al., 2010; Motuzaite-Matuzeviciute et al., 2017, 2020; Zhou et al., 2020; Hermes et al., 2021; Tang et al., 2022; Tian et al., 2022). Currently, I am limited in my comparison of cultivation strategies from plant stable isotope analyses in the IAMC, as few studies exist. However, there are a few notable similarities and differences that can inform a regional understanding of how crops and their associated agricultural techniques dispersed across mountainous Inner Asia.

Compared to the isotopic analysis at Chap (as presented in Chapter 2), I see a similar onset of invested labor into plant cultivation of wheat and barley, however there is a difference in temporal changes in agricultural techniques. Whereas at Chap there is a trend towards intensification, at Tasbas there is a general extensification trend when regarding the $\delta^{15}\text{N}$ values. This also coincides with trends seen in the eastern Tien Shen, where researchers observe an extensification trend in wheat and barley grains that they attribute to growing pastoralism from the 2nd to 1st millennium BCE (Tian et al., 2022). Similar to Chap and sites in the Loess Plateau, northern China (Li et al., 2022), there are taxa-specific cultivation strategies. At Tasbas, water-availability increases for wheat through time, while for barley it remains relatively stable. At Chap, while $\Delta^{13}\text{C}$ values for both wheat and barley increase through time, barley increases more. At both Chap and Tasbas, there are higher $\delta^{15}\text{N}$ values for barley than wheat. The Chap barley increases in $\delta^{15}\text{N}$ values through time, while wheat remains stable. Conversely at Tasbas, $\delta^{15}\text{N}$ values of barley decrease through time.

3.4.6 Conclusion

This study presents an integrated study of macrobotanical and stable isotope data of archaeobotanical remains from the site of Tasbas in southeastern Kazakhstan. Newly analyzed macrobotanical data from the 2023 field season, combined with previously analyzed results from 2011, show a complex crop package that changes through time. Barley becomes the dominate domesticated crop in the Late Bronze Age, with additional evidence of free-threshing wheat (likely bread wheat), broomcorn and foxtail millet, and pea cultivation. Stable isotope analyses of the domesticated assemblage show that from the early establishment of plant cultivation, the crops were grown with labor investment in the form of watering and soil enrichment. Water availability for wheat increases through time, while barley remains stable. There is a general decreasing trend in soil enrichment, more clearly seen in barley than in wheat. Peas were well watered and grew in enriched soil during the Late Bronze Age. This may indicate extensification through time, in the form of decreased manuring or exhausting of soil nutrients.

This evidence counters the previously suggested narrative that agropastoralists at Tasbas conducted extensive plant cultivation (Spengler et al., 2014c, 2014b; Doumani et al., 2015). The data show that for at least the wheat and peas, but also likely the barley to some extent, a dedicated labor system that invested time and effort in providing optimal growing conditions for domesticated crops, all while engaging with mobile pastoralism. These strategies changed over time and were modified for the specific needs of each crop. My results resonate with findings in the Tibetan Plateau, where similar intensive agropastoralism was conducted. Additionally, the different treatments for each crop suggest that the agricultural systems and crops did not necessarily travel as a package across the Inner Asian Mountain Corridor and beyond, but rather, the “package” was localized and modified to fit each community’s specific needs. This further

complicates our understanding of pastoralism and agriculture, showing the complex ways in which ancient mountain communities negotiated the needs of livestock management and cultivation to succeed for thousands of years in the mountains of Inner Asia.

3.5 References

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Chapter 4:

Into Thin Air: prehistoric intensive crop management in high altitude western Tibet

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4.1 Abstract

High-altitude conditions on the Tibetan Plateau are often depicted as an inhospitable environment for conventional farming, yet evidence shows that communities in western Tibet grew ecologically hardy crops such as 6-row barley (*Hordeum vulgare*) by at least the 1st millennium BCE, at locations about 4000 meters above sea level (masl). However, little is

known about the specific cultivation strategies and culinary traditions that these agropastoral communities developed. Stable carbon and nitrogen isotope compositions of grains inform growing conditions and provide much needed insight into the cultivation strategies in such a unique environment. We use $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of archaeologically recovered barley remains to investigate past watering and soil-management strategies. Our results infer high labor investment in manuring and watering in barley farming. This suggests an intensive cultivation system in Western Tibet, 1000 BCE –1000 CE, despite the high-altitude pastoral landscape.

4.2 Introduction

We present a stable isotope study on ancient plant remains from the Tibetan Plateau to explore the cultivation strategies employed by herding communities during the 1st millennium BCE and 1st millennium CE. Through carbon and nitrogen stable isotope analyses of 6-row barley (*Hordeum vulgare*) grains recovered from three sites, representing some of the oldest evidence of grain cultivation in the region, we inquire whether these early highlanders developed intensive cultivation activities in environments optimal for transhumant animal pasturing. We further investigate the influence of growing conditions on barley grain size. Our results from Piyang, Dingdong, and Jiweng provide critical insight into early barley cultivation and labor strategies in western Tibet.

Research shows that this region was at a major crossroad of the trans-Eurasian exchange of crops and livestock, among other commodities, situated along a southern route of the eastern dispersal of the Fertile Crescent cereals, particularly barley (*Hordeum* spp.) (Liu et al., 2017; Lister et al., 2018; Gao et al., 2021). This route parallels (albeit a millennium later) the well-documented northern route through the Inner Asian Mountain Corridor, a series of foothill

locations linking today's eastern Kyrgyzstan, Uzbekistan, and Kazakhstan and western Xinjiang, which were intensively utilized by ancient communities between the 3rd and 1st millennium BCE (Frachetti et al., 2010; Jones et al., 2016b; Liu et al., 2019). The Eurasian food globalization process involved agropastoral communities across Inner Asia cultivating and transporting Southwest Asian crops such as free-threshing wheat (*Triticum aestivum/durum*) and barley and managing livestock such as sheep (*Ovis aries*), goat (*Capra hircus*), horse (*Equus caballus*), and cattle (*Bos taurus*). The spread of broomcorn (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) from their domestication center in northern China westwards to Central Asia and beyond occurred during the 3rd and 2nd millennium BCE (Liu et al., 2018; Hermes et al., 2019; Dal Corso et al., 2022; Endo et al., 2023). Recently published stable isotope results, ceramic impressions, and genetic analyses on related materials are beginning to reveal evidence signifying the incorporation of these newly imported crops and livestock into the indigenous culinary and cultural traditions (Liu and Reid, 2020; Vaiglova et al., 2021; Li et al., 2022; Murakami et al., 2022; Ritchey et al., 2022; Tian et al., 2022; Endo et al., 2023; Sun et al., 2024).

In recent years, there has been an increase in research in the western and central Tibetan Plateau that includes archaeobotanical recovery as one of the primary objectives of study. This resulted in new insight into human and plant interactions that manifested themselves in distinct subsistence strategies, cooking traditions, and ecological interactions. While maintaining these distinct traditions, communities in western and central Tibet were interconnected with broader Eurasia (e.g., Chen et al. 2023; Gao et al. 2021; Tang et al. 2021; d'Alpoim Guedes et al. 2014; Lu et al. 2021; Song et al. 2018, 2021). The Tibetan Plateau provides a unique window into understanding human ingenuity and persistence, as its high elevation presents particular

challenges to human occupation, such as limited growing seasons, harsh weather systems, and reduced oxygen availability.

4.2.1 Plant cultivation on the Plateau

Indeed, humans utilized varying and innovative subsistence strategies to succeed in the high elevations of the Tibetan Plateau. Pastoralism and arable agriculture were first introduced to the eastern Tibetan Plateau between the 4th and 2nd millennium BCE. Domestic pig (*Sus scrofa*) and millet farming spread into the region from the Yellow River and were first concentrated along the northeastern margins of the Plateau (Aldenderfer, 2011; d’Alpoim Guedes et al., 2014; Chen et al., 2015; d’Alpoim Guedes and Aldenderfer, 2020; Ma et al., 2023). Archaeobotanical assemblages from before 1500 BCE are overwhelmingly dominated by foxtail and broomcorn millet, which predate the introduction of wheat (*Triticum* sp.) and barley (*Hordeum* sp.) into the region (Chen et al., 2015; d’Alpoim Guedes, 2015). A different strategy was used in southeastern Tibet. At the sites of Karou and Xiaoenda, for example, there has been unambiguous evidence of mixed hunting and millet farming (Zhang et al., 2019; Song et al., 2021; Lu, 2023). Questions remain as to whether millet grains could be brought to high elevations from lowland farms via trading networks. Macrobotanical remains from the sites of Zongri and Karou support both sides of the argument (Ren et al., 2020; Song et al., 2021). However, human isotope values from Zongri show overwhelmingly clear evidence of substantial millet consumption, likely occurring daily (Cui et al., 2006). While grain trade cannot be ruled out as an explanation, it is unlikely that such trade could sustain human food at a population level, raising questions about local cultivation. By the mid-second millennium BCE, the Southwest Asian domesticates of wheat, barley, and sheep/goats were introduced into eastern Tibet (Chen et al., 2015; d’Alpoim Guedes, 2015). The cold and frost-tolerance of these new crops, particularly barley, the hardiness of the

sheep/goats, and the domestication of high-altitude yaks (*Bos grunniens*) likely facilitated the movement of agropastoralists above 2500 meters above sea level (masl hereafter)(Chen et al., 2015, 2023; Zhang et al., 2022; Tang et al., 2023).

On the other side of the Plateau, communities in the western Tibet were likely closely connected with cultural groups in the Kashmir region of modern-day India as well other regions on the Plateau (Spengler, 2015; Spate et al., 2017; Chen et al., 2024). As early as 2600 BCE, Harappan communities cultivated a diverse crop package including hulled 6-row barley (*Hordeum vulgare* var. *vulgare*), wheat (*Triticum aestivum* and *sphaerococcum*), field-pea (*Pisum arvense*), and rice (*Oryza sativa*) (Pokharia and Saraswat, 2002; Pokharia et al., 2011). In northern Nepal (3000-4000 masl), between 1000 BCE and 1000 CE, there was an early 6-row barley) and buckwheat (*Fagopyrum esculentum/tatarieum*) dominated agropastoral system, with later inclusions of bread wheat (*Triticum aestivum*), broomcorn millet, and pea (*Pisum sativum*) (Knörzer, 2000). Similar ceramic traditions of cord decorations found across the Himalayas may also support this interconnectivity (Chen et al., 2024). By 1500 BCE in central Tibet, agropastoral communities at Changguogou (1400-800 BCE, 2750 masl) and Bangga (1000-800 BCE, 3750 masl) had hulled and naked (*Hordeum vulgare* var. *nudum*) barley, bread wheat, pea, and probably buckwheat (Fu, 2001; d’Alpoim Guedes et al., 2014; Liu et al., 2017; Tang et al., 2021). In southeast Tibet, Wang et al (2021) show that the Nyingchi Region was connected to agropastoralist communities to the west, through the presence of bread wheat, 6-row barley, and peas dated to the 1st millennium BCE. In addition to the three western Tibetan sites presented in this study, the large site of Kaerdong (455–700 cal. CE, 4300 masl) has evidence for a barley-dominated agropastoral system, with the addition of bread wheat and buckwheat (Song et al., 2018). This rapidly growing dataset suggests a possible southern introduction of domesticates

into central and western Tibet coinciding with an early movement of people onto the Plateau (Laurent, 2015; Stevens et al., 2016; Liu et al., 2017; Lister et al., 2018; Gao et al., 2021). This paper begins to address the actual methods used by communities to successfully grow Southwest Asian crop domesticates on the Plateau by examining the labor choices involved in plant cultivation, as measured through stable isotope values of the barley grains themselves at three small agropastoral sites in the Tibetan highland.

4.2.2 Beyond the grain: labor strategies and culinary traditions

Crop management, such as irrigation and manuring, require high labor investment and integration with other tasks, especially in mixed agropastoral economies where mobility for at least some of the population is necessary (Lees and Bates, 1974). There is a potential opposition between the labor strategies necessary for plant cultivation and those of animal pastoralism, particularly in landscapes that lend themselves to herding activities, such as the Tibetan Plateau highlands. Pastoral systems use extensive labor strategies, where productivity is measured by the access to and quality of expansive pasture and the size of the herds grazed on them. Risks are mitigated through herd and grazing land management (Boserup, 1965; Khazanov, 1983; Barfield, 1999; Halstead, 2000; Kradin, 2015). In contrast, with arable farming, production is limited by the amount of suitable land available and its fertility (Boserup, 1965). In this context, intensification is measured by the amount of labor and resources invested per unit area of land through activities such as irrigation, plowing, and fertilizing to buffer against future food shortages (Boserup, 1965; Morrison, 1994; Halstead, 2006, p. 45). Extensification, within the farming context, uses larger plots of land, spreading labor, energy, and time across increasing area (Halstead, 1995, 2000). Macrobotanical remains and plant stable isotope values are useful

proxies for measuring labor strategies and provide an exceptional opportunity to examine the under investigated character of plant cultivation in Western Tibet.

These new domesticates enter not only novel environments but also new cultural settings with their own food preparation techniques. Research across Eurasia identifies distinct cuisines and associated cooking traditions that were formulated before domestication and within which domestication occurred. These culinary practices selected for particular traits exhibited by the domesticated crops. (Sakamoto, 1996; Fuller and Rowlands, 2009, 2011). As the cereal crops moved across Eurasia and into new cuisines, selective pressures modified traits apparent in the grains. For example, during the eastward movement of bread wheat and barley into ancient China, there was a dramatic decrease in grain size as the crops entered a boiling-and-steaming tradition that favored smaller grains (Liu et al., 2016a; Ritchey et al., 2022). The Asian millets, on the other hand, grew in seed size as they move westward into new banking and grinding culinary traditions (Sun et al., 2024). Ritchey et al. (2022) argue that the 6-row barley in Tibet, when compared to the other regions in Central and East Asia, are notably larger and attribute this to a historical tradition of a boiling-free roasting zone in high-elevation Tibet. Boiling whole grains is inefficient in time, labor, and fuel at such high altitudes where low vapor pressure reduces the boiling point of water to 86°C at 4600 masl. A similar trend is seen in foxtail millet on the Plateau (Sun et al., 2024).

An alternative hypothesis to increased grain size could be increasing investment in growing conditions to produce a higher yield with larger grains. Anthropogenically enriched growing conditions can enlarge grain sizes (Savin and Nicolas, 1996; Altenbach et al., 2003; Dupont and Altenbach, 2003; van Bommel et al., 2021; Larsson and Bergman, 2023a). Poor ecological conditions, on the other hand, have been hypothesized to limit plant development and

grain size (Fuller et al., 2017; Motuzaite-Matuzeviciute et al., 2018, 2021a). Experimental work shows variable but generally positive correlations between increased water availability and soil nutrition and grain size in various cereals (van Bommel et al., 2021; Larsson and Bergman, 2023a). Within the context of this growing research, we consider this hypothesis through the analysis of grain size and stable isotope values from three Tibetan Sites in the larger Tibetan dataset from Ritchey et al., (2022).

4.2.3 Archaeological plant stable isotope principles

Plant stable isotope values are currently the most direct method for investigating past growing conditions of plants. In semi-arid/arid environments such as in our study area (<450 mm/annual rainfall), non-native water-demanding cereals are expected to experience water stress to a certain degree (Li et al., 2022). Carbon isotope values ($\delta^{13}\text{C}$) of plant remains, particularly C_3 plants like barley reflect the water availability during plant growth and the grain-filling period (Farquhar et al., 1989; Araus et al., 1997, 1999a; Wallace et al., 2013). $\delta^{15}\text{N}$ values allow for the assessment of soil ^{15}N enrichment processes during plant growth caused by natural and cultural factors including aridity, soil denitrification, and fertilization through middening and manuring (Bogaard et al., 2007; Fraser et al., 2011; Styring et al., 2018). Together, these measurements allow for a direct assessment of past crop agricultural activities of watering and soil maintenance, which have been used to investigate early crop management strategies in the Middle East, Europe, East Asia (Bogaard et al., 2013; Vaiglova et al., 2014a; Styring et al., 2016b, 2018; Li et al., 2022) and recently in the eastern Tianshan Mountains of Inner Asia (Tian et al., 2022). In this study, we use this method to analyze 55 total barley grains from the sites of Dingdong, Piyang, and Jiweng, with each sample representing a single grain (Table 10)

Water availability during photosynthesis directly influences a C₃ plant's ability to assimilate CO₂, which exists in lighter ¹²CO₂ and heavier ¹³CO₂ forms. When plants are well watered, there is free passage of CO₂ through the open stomata on the leaves and the lighter ¹²CO₂ is preferentially assimilated while the heavier ¹³CO₂ is discriminated against (O'Leary, 1988; Girolamo et al., 2014). When growing in water-limiting soils, plants periodically close the stomata to preserve plant moisture, causing CO₂ to be recycled, resulting in higher assimilation of the heavier ¹³CO₂ (O'Leary, 1988; Girolamo et al., 2014). A more negative $\delta^{13}\text{C}$ value of an archaeological grain thus reflects higher water availability during the grain-filling growth period compared to a crop that grew in drier soils (Farquhar et al., 1989; Araus et al., 1999a; Wallace et al., 2013). Stable carbon isotope values are typically reported as $\delta^{13}\text{C}$. However, to compare the values across distinct chronological periods (when the carbon isotope composition of atmospheric CO₂ differed) a conversion to $\Delta^{13}\text{C}$ is needed. This value captures the degree to which a plant discriminated against ¹³C irrespective of the atmospheric composition (Farquhar et al., 1989). We use $\Delta^{13}\text{C}_{\text{plant-air}}$ values as the calculated ¹³C discrimination independent of source CO₂ computed with the equation developed by Farquhar et al. (1989):

$$\Delta^{13}\text{C} = \frac{\delta^{13}\text{C}_{\text{air}} - \delta^{13}\text{C}_{\text{plant}}}{1 + \delta^{13}\text{C}_{\text{plant}}}.$$

After the conversion of results into $\Delta^{13}\text{C}$, the directionality of the water availability changes, with higher $\Delta^{13}\text{C}$ values corresponding to wetter soils. Elevated $\Delta^{13}\text{C}$ values may reflect the use of watering practices such as man-made irrigation, terracing, or strategic planting in wetter soils (Araus et al., 1999a; Ferrio et al., 2005; Wallace et al., 2013).

Table 10. Site, context, and barley recovery information. Macrobotanical data from Tang et al. (2022).

Site	Dingdong	Piyang	Jiweng
Macrobotanical analyses (From Tang et al., 2022)			
Contexts floated	2	4	5
Barley grains recovered			
<i>Hordeum vulgare</i> var. <i>nudum</i> (naked)	413	25	92
<i>Hordeum vulgare</i> var. <i>vulgare</i> (hulled)	62	1	3
indeterminate	330	10	84
Rachis recovered			
<i>Hordeum</i> sp.	36	85	61
Cerealia	0	2	1
C14 date uncal BP	1588 ± 18 BP	2272 ± 19 BP	2254 ± 19 BP
C14 date cal BCE/CE (95.4 % probability)	cal AD 428–541	396–212 cal BCE	391–208 cal BCE
Site type	Year-round agropastoral village	Unclear	Seasonal campsite
This Study			
Grains for isotopic analysis	19 naked, 8 hulled	9 naked	19 naked
Context	2019 DD HD1	2019 PY3 ②	2019 JWT04 HT1
Context description	Fireplace	Trench 04, fireplace	Location 3, layer 2, dense occupation layer

The productivity of the cereal crop can also be improved through the management of soil nutrition. In particular, anthropogenic fertilization of soils, accomplished in ancient times primarily through dung manuring but also through the application of guano and marine biofertilizers, can be detected using $\delta^{15}\text{N}$ values (Szpak et al., 2012; Gröcke et al., 2021). Plant nitrogen isotope values ($\delta^{15}\text{N}$) reflect the isotopic composition of the nitrogen (N) source. For N non-fixers like the barley analyzed in this study, nitrogen is primarily absorbed from the soil. Any enhancements made to the soil, whether of natural or anthropogenic causes, are reflected in higher $\delta^{15}\text{N}$ values of the plant remains (Ambrose, 1991; Bogaard et al., 2007; Fraser et al., 2011; Girolamo et al., 2014; Szpak, 2014). Natural causes for heightened $\delta^{15}\text{N}$ values include

aridity, salinity, and denitrification (Ambrose, 1991; Hartman and Danin, 2010; Szpak et al., 2013). Anaerobic soil conditions and high temperatures can cause soil denitrification which leads to soil bacteria consuming the available oxygen from nitrates, resulting in an increased $\delta^{15}\text{N}$ value of the soil (Farrell et al., 1996; Hartman and Danin, 2010). Temporary waterlogging in floodplains or wadi slopes can result in elevated $\delta^{15}\text{N}$ values of plants grown there (Hartman and Danin, 2010). High-elevation environments, such as the Tibetan Plateau, have unique impacts on $\delta^{15}\text{N}$ values of both the soil and vegetation (see below). Anthropogenic activities to improve fields elevate plant $\delta^{15}\text{N}$ values above the natural baselevel, with values above 6 ‰ in European and southwest Asian contexts reflecting intensive manure application (Bogaard et al., 2007, 2013; Fraser et al., 2011; Szpak, 2014).

Regionally specific nitrogen isotope baselevels can be estimated using archaeological remains of animals that subsist on natural vegetation (such as wild herbivores) (Vaiglova et al., 2022). Based on an estimated trophic offset between diet and consumer tissue, herbivore tissues are approximately 3 - 5 ‰ higher compared to the values of their diet (DeNiro and Epstein, 1981; Minagawa and Wada, 1984). Thus, measured $\delta^{15}\text{N}$ values from bone collagen of archaeological herbivores in the region can provide a local baselevel against which the archaeological plant $\delta^{15}\text{N}$ values can be compared. There are limitations to using local archaeological herbivores to reconstruct baselevels, as the $\delta^{15}\text{N}$ values can vary between individuals, species, and habitat (e.g. hot/dry vs. cool/wet habitats) but similar limitations exist when using modern plant isotope values (environments change over time and are a product of ancient human and natural processes that can influence soil compositions) (DeNiro and Epstein, 1981; Ambrose, 2000; Vaiglova et al., 2022). Unpublished data on archaeological Tibetan deer provide a mean $\delta^{15}\text{N}$ of 4.3 ‰ (n = 12) (Tang et al. 2024). When calculated with the known

offset between trophic levels, this provides a baselevel plant $\delta^{15}\text{N}$ threshold of 0 – 1.3 ‰.

Reported $\delta^{15}\text{N}$ values of modern wild vegetation record a mean of 2.4 ‰ (Yang et al., 2013). We expect the natural non-manured soil $\delta^{15}\text{N}$ values to be approximately between 0 and 2.4 ‰.

4.2.4 Environmental factors for stable isotopes values on the Tibetan Plateau

The extreme ecology and elevation of the Tibetan highlands engenders additional factors to consider before interpreting anthropogenic influences on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, chiefly atmospheric pressure and aridity. Wallace et al. (2013) provide an interpretive framework for interpreting $\Delta^{13}\text{C}$ watering thresholds. This incorporates the known difference in carbon assimilation in barley grown under the same watering regimes. Studies show that atmospheric pressure at high elevations reduces carbon discrimination, therefore increasing $\delta^{13}\text{C}$ (and subsequently, calculated $\Delta^{13}\text{C}$ values) in the plants (Zhou et al., 2011; Szpak et al., 2013). Szpak et al. (2013) find a positive linear correlation with elevation and $\delta^{13}\text{C}$ values in Peruvian C_3 plants ranging from lowland (approximately 10 masl) to highland (>4000 masl) areas (Spearman's $r = 0.879$, $p = 0.001$). There is a positive offset of approximately 2 – 5 ‰ between values from the lowest elevation plants and those at the highest. These findings correlate with those on the Tibetan Plateau, where there is a mean positive increase of 1 – 2 ‰ across a variety of C_3 plants between 2500 – 5500 masl (Zhou et al., 2011). Thus, to accommodate for the atmospheric pressure influence on $\delta^{13}\text{C}$ values on the plant remains from the Tibetan Plateau (>4000 masl), we adjust the calculated $\delta^{13}\text{C}$ ratios for watering bands by a conservative average of +2 ‰ difference (Table 11). We also use modified water categories that follow Li et al. (2022)'s divisions which provide a numeric boundary for Wallace et al. (2013)'s original watering threshold gradient. This provides a more accurate baseline for interpreting water stress in the Tibetan barley (*Hordeum vulgare*). Considering these factors, the Optimal Watering

Threshold (OWT) for $\Delta^{13}\text{C}$ is 15.0 ‰, reflecting the lowest threshold for non-growth restricting watering. Grains that receive more water than necessary are categorized above the Superfluous Watering Threshold (SWT) of $\Delta^{13}\text{C}$ 16.5 ‰.

Table 11. High elevation adjusted $\delta^{13}\text{C}$ and $\Delta^{13}\text{C}$ ratios for the Tibetan Plateau.

Wallace et al., 2013 Thresholds		Li et al., 2022 Thresholds	This paper, adjusted for study area
Original	Adjusted for study area	Original	
$\delta^{13}\text{C}$	$\delta^{13}\text{C} + 2 \text{ ‰}$	$\Delta^{13}\text{C}$	$\Delta^{13}\text{C}$ Water Threshold
-25	-23	18.5	16.5 Superfluous
-24	-22	17	15 Optimal

Environmental factors, such as soil aridity, precipitation, and soil denitrification can influence the $\delta^{15}\text{N}$ values of the plants. Experiments in Peru show that with increasing elevation, $\delta^{15}\text{N}$ of modern foliage reduces by 2 – 6 ‰ (Szpak et al., 2013). This is compounded with a nearly identical negative relationship of $\delta^{15}\text{N}$ values with rainfall, where increased rainfall causes lower $\delta^{15}\text{N}$ values. This relationship is generally understood as driven by soil aridity and annual rainfall rather than solely by altitude. High soil aridity (as opposed to plant water uptake) from low annual precipitation can potentially increase $\delta^{15}\text{N}$ values by 2 – 6 ‰ due to the openness of the nitrogen cycle in arid climates (Szpak et al., 2013). In the Peruvian context, the high elevations have increased rainfall, causing the lower $\delta^{15}\text{N}$ values when compared to the arid, coastal deserts that have higher $\delta^{15}\text{N}$ values (4 – 8 ‰). On the Tibetan Plateau, Yang et al. (2013) find that $\delta^{15}\text{N}$ of modern vegetation increases with decreasing mean annual precipitation. Located within the Plateau temperate monsoon climate zone, the three sites in this study have a mean annual precipitation of less than 450 mm/year (Tang et al., 2022). Based upon the model

proposed by Szpak et al. 2013, this high soil aridity would positively impact $\delta^{15}\text{N}$ values and thus we interpret the results presented in this study accordingly. Yang et al. (2013) and Szpak et al. (2013) both find that mean annual temperature does not seem to influence $\delta^{15}\text{N}$ values at high elevations.

Additionally, the Tibetan Plateau has a high natural abundance of ^{15}N in soil and vegetation (alpine grasses) when compared to the mean global measurements of areas with similar climatic conditions (mean annual precipitation and temperature) (Yang et al., 2013). Yang et al. (2013) measured the mean $\delta^{15}\text{N}$ of vegetation at 2.4 ‰, and the mean $\delta^{15}\text{N}$ of soil at 4.1 ‰, both higher than the mean global measurements of similar climates. They attribute increased ammonia in soil from grazing animals and increased foliar N concentrations as potential mechanisms for this natural abundance. These experiments, while on modern samples, provide data to aid in the interpretations of archaeobotanical assemblages on the Tibetan Plateau. The future addition of archaeological $\delta^{15}\text{N}$ values of low-level herbivores and wild foliage will help clarify these interpretations and provide archaeological baselevels for natural $\delta^{15}\text{N}$.

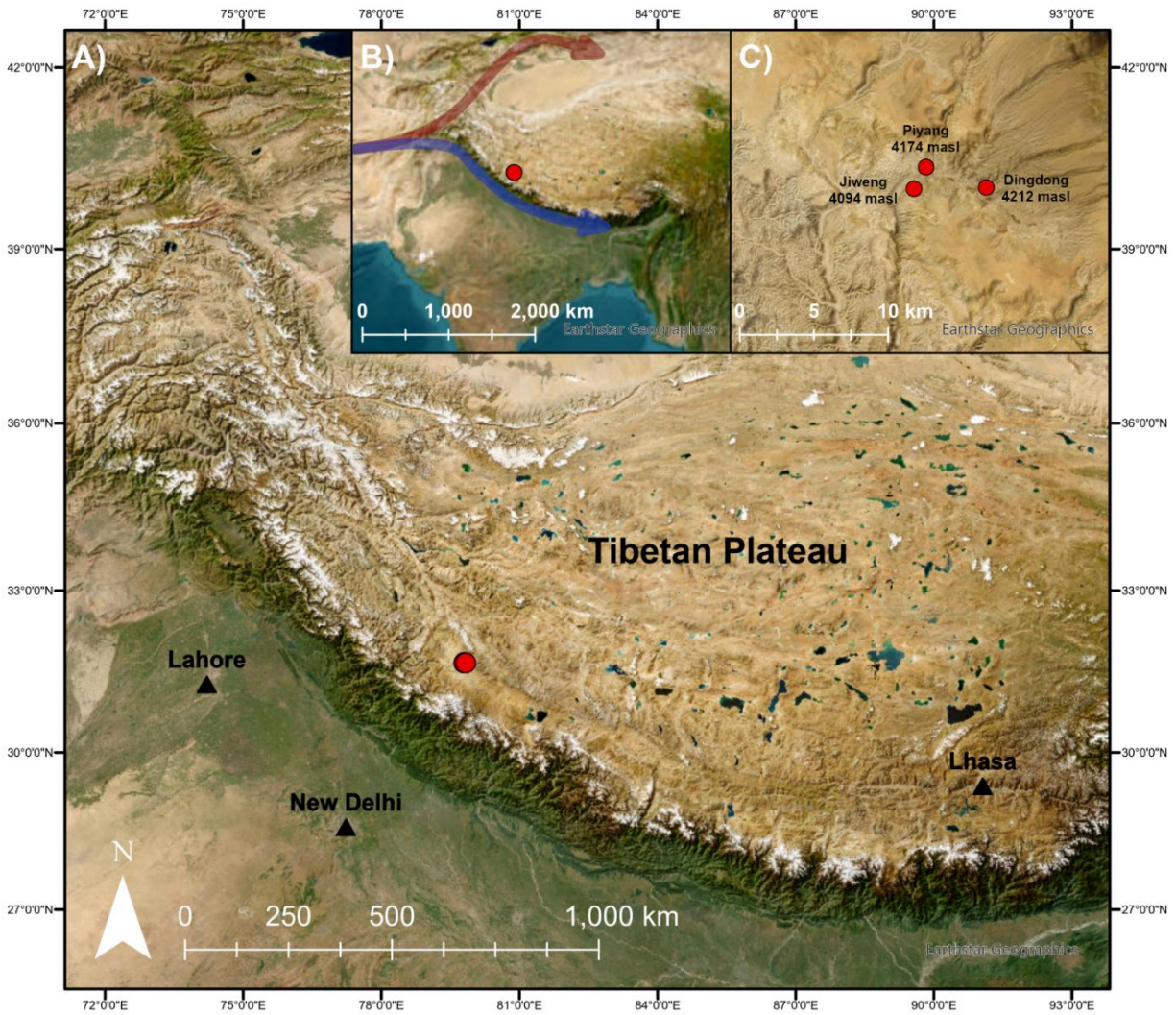


Figure 17. A) Map of study area with B) inset including hypothesized prehistoric food globalization routes: northern trajectory of wheat and barley (red), southern trajectory of barley (blue), and C) an enlarged view of site locations. Basemap data from ESRI World Imagery 2023, Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community.

4.3 Materials and Methods

4.3.1 Excavations and archaeobotanical sampling

Dingdong (4212 masl), Piyang (4174 masl), and Jiweng (4094 masl) are a group of sites located within the broader Piyang Dongga complex (Figure 17). The complex consists of a number of

settlements, cemeteries, and Buddhist monuments that are considered the first examples of permanent occupation in the western Plateau (Fu, 2008; Lu, 2008; Tang et al., 2022). The sites are in Zhada County, Ngari prefecture, along a tributary of the Langqên Zangbo (Upper Sutlej River). Faunal remains of sheep/goats, yaks/cattle, and horses indicate long-term pastoral activities in the site area (Lu, 2008). Excavations in 2019 uncovered new evidence of occupation and agropastoral activities at the sites, coinciding with an agriculture system focused on 6-row barley cultivation (Tang et al., 2022). Evidence of likely local cultivation is evident through the abundant remains of grains, rachises, and culm nodes, indicating crop processing (Table 10). For isotopic sampling, we aimed to choose barley from contexts that had sufficient barley remains present (>10 grains).

Dingdong is a collection of eleven stone structures and three semi-subterranean houses that represent a year-round agropastoral village (~150m²), occupied between 348 cal BC to AD 541. Two flotation samples from fireplaces within these structures were analyzed for macrobotanical remains in 2022. (Tang et al., 2022). These samples included 413 naked (*Hordeum vulgare* var. *nudum*) (41.3 grains/L) 62 hulled (*Hordeum vulgare* var. *vulgare*) (6.2 grains/L), and 330 indeterminate naked/hulled barley (33 grains/L). These were accompanied by 36 barley rachises (3.6 rachises/L). For this isotopic analysis, we sampled 19 naked barley and 8 hulled grains from one of these fireplace contexts (Table 10).

Jiweng is a large stone enclosure (~960m²), occupied between 391 – 208 cal BC. Three trenches from a small test excavation recovered only one artifact, an almost complete red-sand pot, and abundant macrobotanical remains. The layout and lack of artifacts recovered is similar to historical seasonal campsites in the region and suggest a seasonal agropastoral campsite. From three test trenches at Jiweng, 92 naked barley (2.59 grains/L), 3 hulled barley (0.8 grains/L), 84

indeterminate naked/hulled barley (2.37 grains/L), and 61 barley rachises (1.72 rachises/L) were recovered. In this study, we sampled 19 naked barley grains from a fireplace context located in Trench 4 (Table 10).

During construction in the village of Piyang, a soil section was exposed containing abundant ceramics, animal remains, and charcoal. Three subsections with dense deposits were sampled for floatation, totaling 6 samples. Due to the rescue nature of this sampling, it is unclear the site type of the archaeological deposits at Piyang, dated to 396-212 cal. BC. From these samples, 25 naked barley (4 grains/L), 1 hulled (0.16 grains/L), 10 indeterminate naked/hulled barley (1.6 grains/L), and 85 barley rachises (13.6 rachises/L) were recovered. The low number of overall grains recovered limited our sampling for isotopic analyses. As such, we sampled 9 naked barley grains from layer 2, which had the most grains ($n = 20$) recovered (Table 10).

Naked and hulled barley and indeterminate cereal grains (cereal) were the only domesticated grains recovered from all three sites. The wild taxa were identified to the family level, with a few to the genus level, which limits our ability to determine if they are representative of arable weed taxa. The families identified include Amaranthaceae, Brassicaceae, Cyperaceae, Poaceae, Polygonaceae, Rosaceae, and Solanaceae. At the genus level, *Chenopodium* sp, *Capsella* type, and *Bromus* sp., may represent common arable weeds such as *Chenopodium album*, *Capsella bursa-pastoris*, and *Bromus* spp., if identification were possible to the species level. Some of the wild taxa, e.g. *Chenopodium* sp., Fabaceae, and *Potentilla/Fragaria* spp., depending on the species, could have been collected as a source of wild food. Some of these taxa, particularly *Chenopodium* sp., are also consumed by livestock and could have entered the macrobotanical record through dung burning for fuel (Spengler, 2018).

See Tang et al. (2022) for more detailed descriptions of the archaeological excavations and analysis of the macrobotanical assemblages from all three sites.

4.3.2 Grain preservation and charring

We analyzed barley grains that were charred through exposure to high temperatures and potentially directly to fire that caused the whole grain to undergo a chemical process that removes water vapor and volatile organic compounds from the grain matrix. This leaves a black carbon material, char, preserving the archaeological grain. In general, this charred grain maintains the carbon and nitrogen isotopic values from prior to charring, albeit with known charring offsets, varying with the temperature and duration of charring (Nitsch et al., 2015; Stroud et al., 2023b). The known charring offsets (averaged across temperatures and duration: $\delta^{13}\text{C}$ by + 0.11 ‰ and $\delta^{15}\text{N}$ by + 0.33 ‰, (Nitsch et al., 2015) are lower than the conservative 1 ‰ estimates used in most paleodietary studies (following Fraser et al. 2013) and consequently have little impact on our data interpretation. It is nonetheless important to consider the potential fractionation occurring during carbonization, particularly when reconstructing past agricultural practices using modern-day isotopic values or comparing the isotopic values from charred archaeological material to that of uncharred material.

The charring temperatures need to be considered, as they impact isotopic value at various rates depending on charring temperature and duration (Fraser et al., 2013; Nitsch et al., 2015; Stroud et al., 2023a). Well-preserved grains are those that have been charred within optimal charring conditions (Styring et al., 2013; Charles et al., 2015; Vaiglova et al., 2022; Stroud et al., 2023a). Following these guidelines, particularly those provided by Stroud et al. (2023a), we visually examined grain surface and cross sections, photographed, and categorized each grain as

“poor”, “borderline”, and “good” preservation. Photo examples are provided in Appendix 1. and categorizations in Supplementary Table 16. We ran all grains for isotopic analysis, regardless of qualitative charring status. We then compared this qualification to the isotopic results to see if the charring status correlates with isotopic value. Visual inspection of grain charring and isotopic results by site show no apparent clustering or pattern (Figure 18). We estimated 95 % confidence intervals (CIs, reported as [lower level, upper level]) around the means of charring status group measurements to further interrogate a potential relationship between charring status and isotopic result (Supplementary Table 17, Supplementary Figure 12).

The mean $\delta^{13}\text{C}$ values for each charring status are very similar, with nearly identical CIs: good 15.9 ‰ [15.3, 16.5], $n = 10$, borderline 16.0 ‰ [15.5, 16.5], $n = 14$, and poor 15.9 ‰ [15.6, 16.3], $n = 31$. The mean $\delta^{15}\text{N}$ values for poor and borderline are similar: 14.5 ‰ [13.7, 15.3] and 15.10 ‰ [13.9., 16.3], respectively. The mean of the good category is higher at 17.1 ‰ [15.7, 18.5], with the lower CI overlapping with the upper CI of borderline. There is a difference between good and poor mean $\delta^{15}\text{N}$ values, with a mean difference of -2.6 ‰ [-4.2, -1.0]. This suggests, given the small sample size of the data collected, the difference between the mean $\delta^{13}\text{C}$ values of good and poor grains is plausibly anywhere between -4.2 ‰ and -1.0 ‰. There is considerable overlap between CIs of good and poor grains, suggesting that the differences in means may not be notable. There is a broad spread in the poor grains (over a 10 ‰ difference between the lowest and highest values) compared to the good grains (~ 5 ‰). This could, in part, be influenced by the much higher sample size for poor grains ($n = 31$) than good grains ($n = 10$). If we were able to increase the good grain sample size, it is possible we would see a similar spread in the $\delta^{15}\text{N}$ values. Based on the collected data, we conclude that there are no plausible differences between the $\delta^{13}\text{C}$ means of the different charring categories and that all isotopic

measurements, regardless of charring status, are appropriate for our analyses. While there is a difference between the $\delta^{15}\text{N}$ means of good and poor grains that should be considered, due to the limited materials available for additional analyses, we have included all grains within our study.

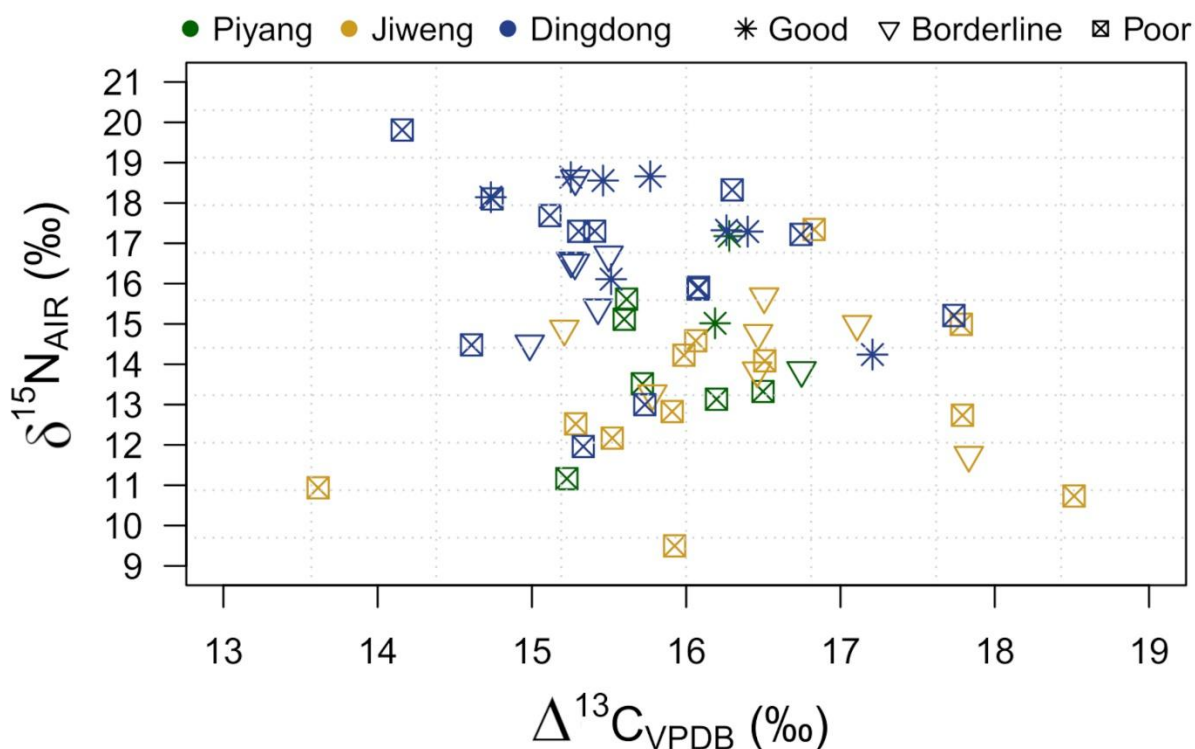


Figure 18. Scatterplot of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values categorized by site and grain preservation status.

4.3.3 Grain pretreatment and isotopic analysis

We selected well-preserved barley grains (determined from surface texture and wholeness of the grain) for isotopic analysis. After cross-sectioning and photographing the grains for recording the charring status of the internal matrix, as previously discussed, we prepared the grains for individual grain isotopic analyses following Vaiglova et al. (2014b)'s pretreatment procedure using a gentle acid wash to remove any exogenous soil carbonates. Each grain was cleaned of

any visible surface contaminants, crushed to a fine powder, and weighed. We then soaked each sample with 0.5 M HCl acid and heated them at 80 °C for 30 minutes. After 3 washes with deionized water, samples were dried in the vacuum freezer for 8 hours. 800 µg of the dried samples were placed into tin capsules. We conducted the carbon and nitrogen stable isotope analyses using an Elemental Analyzer coupled to a Thermo Delta V Plus Continuous Flow Isotope Ratio Mass Spectrometer (EA–IRMS) housed at the Department of Earth, Environmental, and Planetary Sciences at Washington University in St. Louis, USA. We normalized the raw $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values relative to VPDB and AIR, respectively, with the international standards of USGS 40 ($\delta^{13}\text{C} = -26.4\text{‰}$, $\delta^{15}\text{N} = -4.5\text{‰}$) and USGS41a ($\delta^{13}\text{C} = +36.6\text{‰}$, $\delta^{15}\text{N} = -4.5\text{‰}$). Two in-house standards were used for linearity and check standard: acetanilide ($\delta^{13}\text{C} = -29.5\text{‰}$, $\delta^{15}\text{N} = +47.6\text{‰}$) and BR millet (Bob’s Red Mill millet flour; $\delta^{13}\text{C} = -13.2\text{‰}$, $\delta^{15}\text{N} = +3.3\text{‰}$). No replicates were conducted on the archaeological samples, due to the limited mass per grain sample after pre-treatment processing.

Precision ($u(Rw)$) was determined to be $\pm 0.07\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.08\text{‰}$ for $\delta^{15}\text{N}$. Accuracy or systematic error ($u(bias)$) was determined to be $\pm 0.14\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.20\text{‰}$ for $\delta^{15}\text{N}$ based on calibration standard and check standard measurements. Using the equations from Szpak et al. (2017), the total analytical uncertainty was determined to be $\pm 0.16\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.22\text{‰}$ for $\delta^{15}\text{N}$. One BR millet check standard produced unexpectedly different values (-21.75‰ compared to the expected -13.18‰ for $\delta^{13}\text{C}$ and 15.04‰ compared to the expected 3.28‰) and was removed from uncertainty calculations. This anomalous check standard may be due to the possible slight heterogeneity of the sample or instrument drift (Szpak et al., 2017). If included in the calculations, the total analytical uncertainty is $\pm 2.1\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 2.8\text{‰}$ for $\delta^{15}\text{N}$.

We used R (version 4.3.1) to create graphs. R packages included ggplot2, esci, and EnvStats, with additional packages for aesthetics (Millard, 2013; Wickham, 2016; R Core Team, 2023; Calin-Jageman, 2024). We used Jamovi (Version 2.4) to calculate confidence interval statistics and plots (The Jamovi Project, 2023).

4.4 Results

Results of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analyses are reported in Table 12 and displayed as boxplots and CIs in Figure 19. We use a 95 % confidence interval for all analyses. The $\delta^{13}\text{C}$ values of grains from Jiweng record the highest mean (16.7 ‰, [16.1, 16.9], n=19), followed by Piyang (16.2 ‰, [15.7, 16.6], n=9), and Dingdong (15.8 ‰, [15.5, 16.1], n=27). With the adjusted watering bands for a high-elevation atmospheric effect, all three sites have grains that measure above the optimal watering threshold. Four grains from Dingdong measure below the OWT and four from Jiweng measure above the SWT. Overall, the most observable difference in $\delta^{13}\text{C}$ values between sites lies in the higher $\delta^{13}\text{C}$ values from Jiweng. The mean difference between Jiweng and the combined values of Dingdong and Piyang is -0.6 ‰, [-1.1, 0.0] (Supplementary Table 18, Supplementary Figure 13). This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{13}\text{C}$ values at Jiweng and the other two sites is plausibly anywhere between -1.1 ‰ and 0.0 ‰. There is some overlap between the CIs of the values from Jiweng and the Dingdong/Piyang data. This suggests that there is a possible difference between the mean values of the two sets of groups. The difference is more notable between Jiweng and Dingdong than any other pairing, with a mean difference of 0.9 ‰, [0.3, 1.5]. This suggests, given the small sample size of the data collected, the difference between the mean $\delta^{13}\text{C}$ values at Jiweng and Dingdong is plausibly anywhere between 0.3 ‰ and 1.5 ‰. There is no overlap

between the CIs of the values from Jiweng and Dingdong, suggesting that there is a notable difference between the higher mean values of Jiweng from that of Dingdong.

Table 12. A summary of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, mean, standard deviation (SD), 95 % confidence intervals (CIs), median, and morphology metrics of barley grains (*Hordeum vulgare*) from Dingdong, Jiweng, and Piyang. Note: Due to preservation and taphonomic processes, grains from Dingdong are missing 3 length and 1 breadth measurements, grains from Jiweng are missing 1 length and 1 breadth measurements, and a grain from Piyang is missing 1 length measurement.

Measurement	Dingdong all grains n = 27	Dingdong <i>Hordeum vulgare</i> var. <i>nudum</i> n = 19	Dingdong <i>Hordeum vulgare</i> var. <i>vulgare</i> n = 8	Jiweng n=19	Piyang n=9
$\Delta^{13}\text{C}$ mean $\pm$ SD (1 σ) (‰)	15.8 $\pm$ 0.9	15.6 $\pm$ 0.9	15.6 $\pm$ 0.8	16.7 $\pm$ 1.1	16.2 $\pm$ 0.6
95 % CI [LL, UL]	[15.5, 16.1]	[15.3, 16.0]	[14.9, 16.3]	[16.1, 16.9]	[15.7, 16.6]
median	15.5	15.4	15.4	16.9	16.2
$\delta^{15}\text{N}$ mean $\pm$ SD (1 σ) (‰)	16.6 $\pm$ 1.9	17.0 $\pm$ 1.9	15.9 $\pm$ 0.6	13.5 $\pm$ 1.9	14.2 $\pm$ 1.7
95 % C [LL, UL]	[15.9, 17.4]	[16.0, 17.9]	[14.5, 17.3]	[12.5, 14.4]	[12.9, 15.5]
median	17.2	17.3	15.6	13.8	13.8
Length mean $\pm$ SD (1 σ) (mm)	5.91 $\pm$ 0.49	5.74 $\pm$ 0.39	6.25 $\pm$ 0.52	5.19 $\pm$ 0.62	4.77 $\pm$ 0.47
95 % C [LL, UL]	[5.7, 6.12]	[5.53, 5.95]	[5.82, 6.69]	[4.88, 5.5]	[4.38, 5.16]
median	5.85	5.74	5.75	5.2	4.79
Breadth mean $\pm$ SD (1 σ) (mm)	3.06 $\pm$ 0.47	3.25 $\pm$ 0.35	2.56 $\pm$ 0.29	2.24 $\pm$ 0.41	3.14 $\pm$ 0.36
95 % C [LL, UL]	[2.87, 3.25]	[3.10, 3.45]	[2.32, 3.81]	[3.25, 3.44]	[3.1, 3.41]
median	3.1	3.17	2.46	3.15	3.05
Thickness mean $\pm$ SD (1 σ) (mm)	2.28 $\pm$ 0.38	2.47 $\pm$ 0.26	1.83 $\pm$ 0.21	2.34 $\pm$ 0.29	2.11 $\pm$ 0.32
95 % C [LL, UL]	[2.13, 2.43]	[2.34, 2.60]	[1.65, 2.01]	[2.2, 2.48]	[1.87, 2.35]
median	2.34	2.46	1.81	2.31	2.07
Length/Breadth ratio mean $\pm$ SD (1 σ) (mm)	2.0 $\pm$ 0.42	1.76 $\pm$ 0.18	2.47 $\pm$ 0.68	1.6 $\pm$ 0.2	1.51 $\pm$ 0.06
95 % C [LL, UL]	[1.82, 2.18]	[1.67, 1.86]	[2.16, 2.78]	[1.5, 1.71]	[1.46, 1.56]
median	1.88	1.72	2.65	1.57	1.53

Dingdong grains have the highest mean $\delta^{15}\text{N}$ of the group (16.6 ‰, [15.9, 17.4], n=27), followed by Piyang (14.2 ‰, [12.9, 15.5], n=9), and Jiweng (13.5 ‰, [12.5, 14.4], n=19). All are well above the calculated natural baselevel of 0 – 2.4‰ from archaeological herbivores and wild seed remains (Yang et al., 2013; Tang et al. 2024 in prep). When compared to experiments conducted in modern farm settings in England and Germany, where heavily manured (+35 tons of manure/ha) barley and wheat had a mean value of 8 ‰ $\delta^{15}\text{N}$, all barley grains from this study fall well above this highly-manured threshold (Bogaard et al., 2013). Overall, the most observable difference in $\delta^{15}\text{N}$ values between sites is the increased mean of Dingdong. The mean (Supplementary Table 19, Supplementary Figure 14). This suggests that, given the small sample size of the data collected, the mean difference between the $\delta^{15}\text{N}$ values at Dingdong and the other two sites is plausibly anywhere between -3.9 ‰ and -1.8 ‰. As the lower limit of the CI for Dingdong is 15.9 ‰, and the upper limit of the CI for the combined Jiweng/Piyang data is 13.1 ‰, this difference is notable due to the lack of overlap between the groups. Further, when compared to a similar archaeological plant stable isotope study in Xinjiang, China, the samples from this study, while variable, fall above Li et al.'s (2022) calculated threshold for high nutrient-rich soil condition of 8.5 ‰ $\delta^{15}\text{N}$ for a region (Zhuanglang county) that receives a mean annual precipitation of 550 mm.

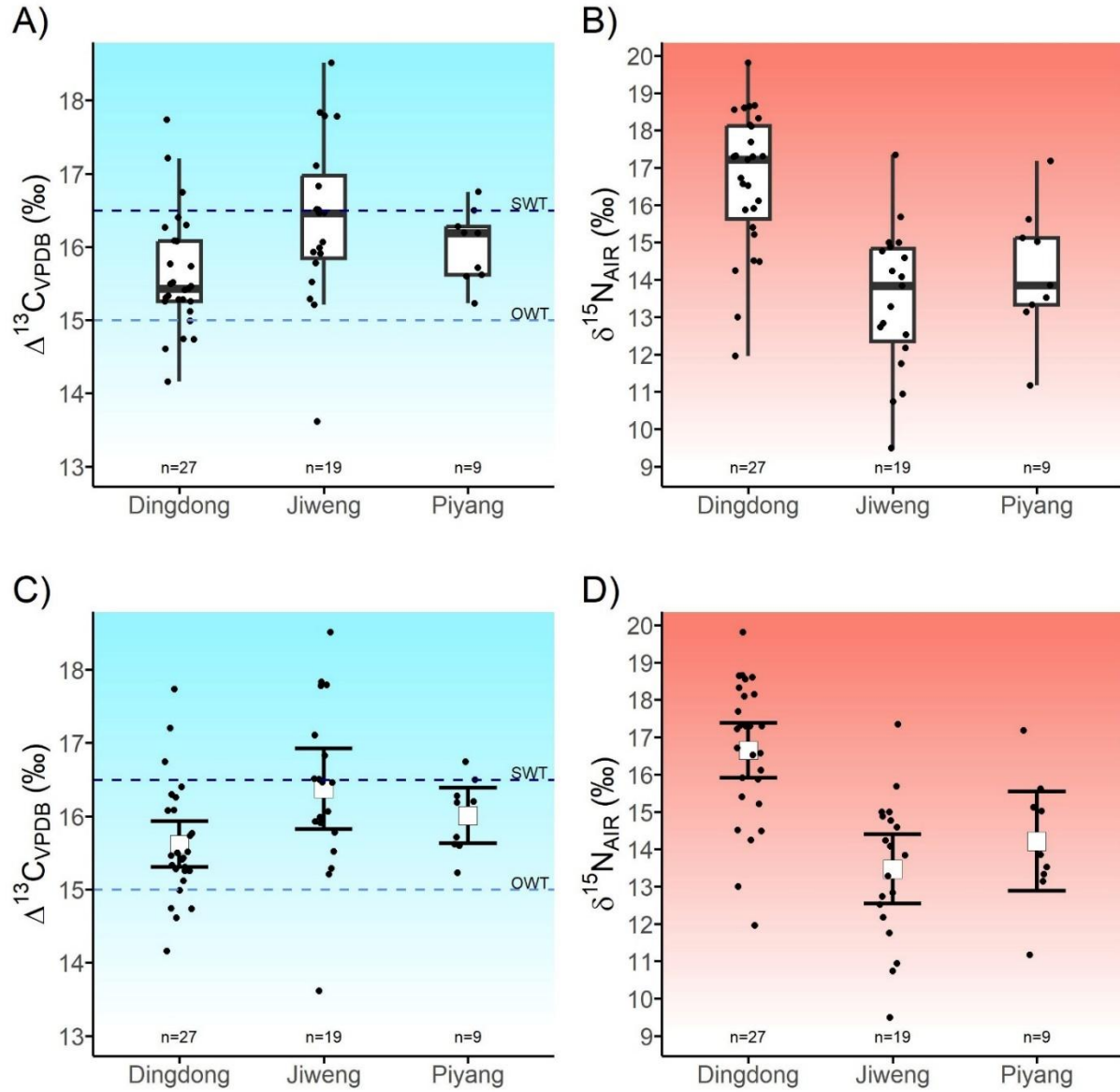


Figure 19. A) Boxplots of $\Delta^{13}\text{C}$ values and B) $\delta^{15}\text{N}$ values of barley grains from Piyang, Dingdong, and Jiweng. C) Independent groups contrast figure comparing the 95 % confidence intervals (CIs) of $\Delta^{13}\text{C}$ values and D) $\delta^{15}\text{N}$ values of barley grains from Dingdong, Jiweng, and Piyang; error bars represent CIs and squares represent group means. Horizontal lines in A) and C) represent high-elevation-adjusted (+2 ‰ $\Delta^{13}\text{C}$) thresholds of optimal watering (OWT), and superfluous watering (SWT) thresholds. Color gradients reflect increasing water input and soil nitrogen levels

At Dingdong, we analyzed both hulled and naked grains. CIs show no notable difference in the $\delta^{13}\text{C}$ values between naked (15.6 ‰, [15.3, 16.1], n=19) and hulled grains (15.9 ‰, [14.5, 17.2], n=8) with a mean difference of 0.1 ‰, [-0.6, 0.8] (Supplementary Table 20, Supplementary Figure 15). Mean $\delta^{15}\text{N}$ values of naked barley (17.0 ‰, [16.1, 17.8], n=19) are higher than those of hulled barley (15.9 ‰, [14.5, 17.2], n=8), with a mean difference of 1.1 ‰, [-0.5, 2.7]. Given the limited sample size, the difference between $\delta^{15}\text{N}$ values of naked and hulled barley at Dingdong is plausibly anywhere between -0.5 ‰ and 2.7 ‰. However, there is considerable overlap in CIs between the two groups, suggesting there is not a meaningful difference for either $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$.

Barley grain sizes at Piyang, Jiweng, and Dingdong are on average very large, in length and breadth, when compared to other archaeological grains in central and eastern Eurasia (see Ritchey et al., 2022 for a robust regional analysis). However, the individual grain metrics vary and span the spectrum of domesticated barley grain size, from the shortest at 4.03 mm to the longest at 7.01 mm (Supplementary Table 21). Figure 20 presents scatter plots of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values versus (vs.) grain length, breadth, and thickness. We assessed linear correlations of length, breadth, thickness, and length/breadth ratio vs. stable isotope value using Pearson's r (Supplementary Table 21). However, due to the small sample size, correlation cannot be estimated with much precision. Overall, the results of the Pearson's r suggest poor correlation between grain metrics and isotope value. Two correlations of Piyang grains have Pearson's r that suggest moderate correlation: $\delta^{15}\text{N}$ vs. thickness, $r(7) = .55$, $n = 9$ [-0.21, 0.88] and $\delta^{15}\text{N}$ vs. breadth, $r(7) = .46$, $n = 9$ [-0.32, 0.85]. However, the wide confidence intervals suggest that the estimates of the true correlation have low precision and could be anywhere from -0.21 (suggesting poor negative correlation) to 0.88 (suggesting strong positive correlation) for $\delta^{15}\text{N}$

vs. thickness and anywhere from -0.32 (suggesting poor negative correlation) to 0.85 (suggesting strong positive correlation) for $\delta^{15}\text{N}$ vs. breadth. At Dingdong, both hulled and naked barley were analyzed. Hulled grains at Dingdong are generally narrower in breadth and shorter in thickness than the naked barley (Supplementary Table 21, Supplementary Figure 15). When analyzed separately, there are two correlations that suggest moderate positive correlations: $\delta^{15}\text{N}$ vs. breadth, $r(6) = .42$, $n = 8$ [-0.43, 0.86] and $\Delta^{13}\text{C}$ vs. breadth, $r(6) = .47$, $n = 8$ [-0.38, 0.87] (Supplementary Table 21). Additionally, one correlation suggests a moderate negative correlation: $\Delta^{13}\text{C}$ vs. L/B ratio, $r(6) = -.51$, $n = 8$ [-0.89, 0.33] (Supplementary Table 21). The large confidence intervals indicate that the true correlations have low precision for each of these analyses. All other correlations fall below a Pearson's r of 0.4.

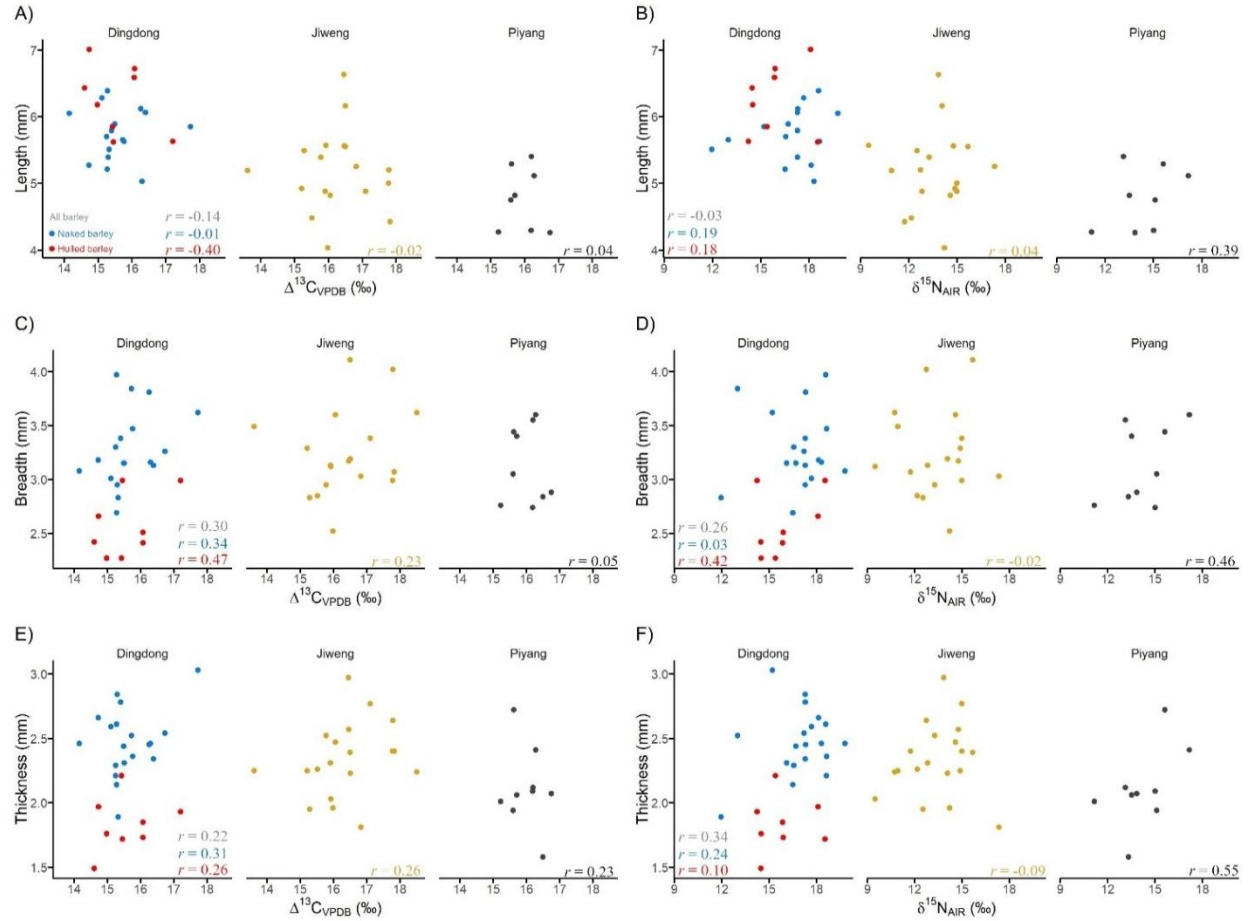


Figure 20. Scatterplots of grain measurements (in mm) vs. stable isotope value for each study site, with the calculated Pearson's *r*: A) Δ¹³C vs. length; B) δ¹⁵N vs. length; C) Δ¹³C vs. breadth; D) δ¹⁵N vs. breadth; E) Δ¹³C vs. thickness; F) δ¹⁵N vs. thickness. For Dingdong, red circles represent hulled barley (*Hordeum vulgare* var. *vulgare*) and blue circles represent naked barley (*Hordeum vulgare* var. *nudum*) grains; the grey Pearson's *r* is for all Dingdong grains combined.

4.5 Discussion

Stable isotope analyses of ancient crop remains allow for the assessment of their growing conditions (e.g., Ferrio et al., 2005; Fraser et al., 2011b; Styring et al., 2015). In certain anthropogenic contexts, elevated carbon and nitrogen isotope values (Δ¹³C and δ¹⁵N) indicate dedicated labor input to both watering (through irrigation activities) and manuring, which in

normal circumstances, correspond to agricultural intensification rather than extensification (Bogaard et al., 2013). In an agropastoral setting, relatively lower labor input in watering and manuring could signify a deemphasis on cultivation activities. Within communities focused more on herding practices for food production, crops may be grown opportunistically and/or extensively, as seen archaeologically in Tian et al. (2022). This study measured and calculated the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of barley grains from the western Tibetan Plateau sites of Jiweng, Dingdong, and Piyang. The results indicate a managed crop cultivation system, where ancient herders invested time, energy, and labor into cultivating barley in the high-elevation western Tibetan Plateau. Furthermore, in considering the role that culinary traditions play in barley grain metrics (Ritchey et al. 2022), we presented a comparison between grain metrics and grain isotope values (Figure 20). No obvious relationship has been observed. Due to the small sample size, we are unable to make meaningful interpretations from the data. The relatively recent inclusion of systematic macrobotanical sampling on the Tibetan Plateau inhibits a larger analysis at this time. Future work will no doubt expand our understanding of early agricultural labor strategies when isotope analysis with a larger assemblage of macrofossils becomes available, which will increase the precision of mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ estimates of ancient crop remains in the study area.

4.5.1 Ancient herders watered their barley crops

$\delta^{13}\text{C}$ values of barley grains from the three investigated sites indicate that the crop was grown in fairly well-watered soils. A few grains are above the optimal watering threshold, while the remaining grains are above the superfluous watering threshold. It should be noted that barley is less water-demanding than other Southwest Asian domesticates, such as wheat, and can grow in more arid environments (Miller, 2003). It is, therefore, particularly interesting to observe elevated $\delta^{13}\text{C}$ ratios in the barley from all three sites when, ostensibly, they could have

successfully grown without additional watering. Modern annual rainfall in the region is between 300–450 mm (Tang et al., 2022). Paleoclimate reconstructions of temperature and precipitation during the late Holocene, after 4400-4500 BP, suggest aridification in the region that stabilized into a climate that is similar to today (Gasse et al., 1991, 1996; Hou et al., 2012). There was a significant cooling period ca. 2100 BP, with annual rainfall between 300-350mm (Hou et al., 2012). Given such a semi-arid environment, our results support a cultivation system that utilized anthropogenic water sources. This could include irrigation of fields, as commonly applied today across the Plateau, or strategic planting of barley crops in naturally wetter areas. The lower $\delta^{13}\text{C}$ ratios at Dingdong, which was occupied a millennium later during the 5th century AD, might indicate a change in barley cultivation strategies with decreased investment in water-management systems through time. Our sample size is too small to permit such an inference, but such a scenario would resonate with what has been recently observed in eastern Tianshan and eastern Inner Mongolia where communities turned to extensification of plant cultivation corresponding with an increase in pastoralism (Tian et al. 2022, Sun et al. in prep.).

4.5.2 The question of manuring

As previously mentioned, plant $\delta^{15}\text{N}$ values reflect soil conditions during plant growth. When compared to the average high-manured $\delta^{15}\text{N}$ values in experiments or other studies in the surrounding regions, the Tibetan barley grains are extremely ^{15}N enriched (Fraser et al., 2011; Kanstrup et al., 2011b; Styring et al., 2016a; Tian et al., 2018). It is possible that the barley was grown in areas subject to seasonal flooding which may cause a waterlogged environment susceptible to denitrification and thus higher grain $\delta^{15}\text{N}$ values. In an experiment in the eastern Mediterranean, Hartman and Danin (2010) find a mean increase of 3.5‰ $\delta^{15}\text{N}$ in dry wash C_3 plants ($5.23 \pm 2.4\text{‰}$) as compared to C_3 plants grown on exposed ridges ($1.7 \pm 3.2\text{‰}$). Even

when considering the highest 6 ‰ offset for aridity (Szpak et al., 2013), the naturally elevated enrichment of the Tibetan Plateau at 2.9 ‰ (Yang et al., 2013), and the influence of denitrification, the mean $\delta^{15}\text{N}$ values range between 13.5 – 16.5 ‰ and are still well above the highly manured threshold proposed by Fraser (Fraser et al., 2011) and that of the local baselevel. The high values could indicate over-manuring that would limit yield but still successfully produce grains (as seen by Szpak et al. (2012) in maize experimentally manured with seabird guano). In an experimental study by Styring et al. (2016a) of Moroccan farming plots, they record $\delta^{15}\text{N}$ values of barley grains ranging between 12.5 – 15.4 ‰ from highly manured and irrigated fields. These data resonate with the results in our study, especially when considering the additional influences of natural soil conditions on the Plateau. This signifies that the ancient herders improved their cultivated fields, likely through animal manure. The $\delta^{15}\text{N}$ results are variable, which could be the result of variation within a cultivation plot, cultivation in different soil conditions, over different growing seasons, different geographical locations and natural influences, or variable application of manure across the field(s) (Groffman and Hanson, 1997; Finlay and Kendall, 2008; Fraser et al., 2011; Styring et al., 2016a).

4.5.3 Tibetan Cultivation in Context

The prehistoric food globalization process likely triggered a series of transformations in subsistence strategies across Eurasia, resulting from the incorporation of non-locally domesticated crops and livestock into the indigenous systems. As part of this process, barley cultivation entered western Tibet, likely via the Kashmir along a southern dispersal route (Liu et al., 2017; Lister et al., 2018; Gao et al., 2021). In a separate, northern pathway, barley – along with wheat – also moved along the mountainous region of Inner Asia, eastwards to Eastern Tianshan and the Hexi Corridor (Liu et al., 2017; Lister et al., 2018). While currently there is no

other research on crop labor investment available to compare to on the Tibetan Plateau, our findings can be contextualized with barley stable isotope research from regions connected to Tibet through this prehistoric food globalization process.

North of the Plateau, a recent study shows a similar pattern of early investment in barley cultivation (Tian et al., 2022). During the Bronze Age, communities living in the piedmont zones of the eastern Tianshan provided optimal watering conditions to their 6-row barley crops, whether through simple channel irrigation or opportunistic planting. Additionally, the fields were likely manured. This resonates with our findings in Western Tibet. During the later occupational phase, communities in eastern Tianshan experienced a transition in cultivation strategies from intensification to extensification. Such a trend is documented in crop $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, signifying less water and manuring inputs associated with increased weed taxa (Tian et al. 2022). The researchers attribute this to an increasing reliance on nomadic pastoral lifeways resulting in a reduced labor budget for plant cultivation. Sheng et al. (2021) document a similar trend in the $\delta^{15}\text{N}$ values of broom corn and foxtail millet at Bronze Age Shimao, where early heavily manured millet cultivation transitioned to a more extensive system, incorporating more herded livestock (sheep/goats and cattle) as the climate changed and fields were possibly exhausted by the earlier intensive agriculture. The transition to extensive cultivation and pastoralism stands in contrast to the western Tibet data, which shows a dedicated pastoral system coinciding with an intensive barley cultivation regime. Further east on the Loess Plateau in Zhuanglang County, isotopic analyses of multi-crop agricultural communities spanning 6000 BCE to 1800 CE indicate a separate management system for free-threshing wheat and 6-row barley, where wheat is intensively managed through watering and manuring, while barley is grown under water stress and no significant shifts over time were observed (Li et al., 2022).

Turning to Southwest Asia, research finds different drivers for changes seen in cultivation strategies. In northern Mesopotamia, there was a reduction in manuring through time that correlates with increased site size, from the 6th to 3rd millennium BCE. Additional factors that likely influenced this change were extensification from the increase of land under arable production and the development of a specialized pastoralist economy that reduced the availability of animal manure (Styring et al., 2017). In western Tibet, however, agropastoralists likely invested heavily in barley crops while simultaneously engaging in highland pastoralism. As discussed by Tang et al. (2022), communities at small sites (including the study sites in this paper) in western Tibet utilize dedicated monocropping of barley combined with livestock herding, whereas larger sites show more crop diversity. Zhang et al. (in press) show a unique pastoral system in central Tibet where high labor investment associated with foddering and water provisioning was common practice in high-altitude environments. The intensive cultivation signatures of barley from this study lend further support to the argument that these agropastoralists utilized a risk-reduction strategy of dedicated barley cultivation and intensified herding practice. These dissimilarities in the treatment of barley across regions complicate our notions of strict mobile pastoralism and settled agriculture when investigating ancient subsistence patterns and call for further studies into the range of choice and possibilities available.

4.6 Conclusion

In this paper, we analyzed the stable carbon and nitrogen isotope values of barley grains recovered from three western Tibetan sites: Piyang, Jiwen, and Dingdong. The results suggest that when barley was first introduced into the region, the communities used a shared intensive

cultivation strategy to successfully grow barley above 4000 masl. Agropastoralists at Jiweng, Piyang, and Dingdong likely manured their fields for barley cultivation. Piyang and Jiweng provided additional water to the crops, either by irrigating the plants or strategically planting at locations with higher soil water retention. The community at Dingdong did not supplement watering for their barley as much as the other two sites but still ensured adequate water for their barley. Further work on the wild taxa to identify possible arable weeds to the genus and species level would add additional information regarding cultivation strategies that could be compared to the isotopic results.

At a broader regional level, our results resonate with the farming systems commonly seen in prehistoric northern China, where early farmers invested labor significantly into the cultivation of wheat, barley, and foxtail and broomcorn millet (Sheng et al., 2021; Li et al., 2022). Our results, however, differs from the extensification trend later seen in northern China and in eastern Tianshan that has been recently documented by isotope analysis (Tian et al. 2022). Additionally, we compared the isotopic results with the morphometrics of the barley grains to ascertain the role of growing conditions in grain size. We did not find any meaningful correlation between isotopically inferred growing conditions and barley grain metrics. Admittedly, the sample size is small, but already at the limit of destructive work allowed due to the limited number of grains recovered. When the opportunity arises, future isotopic and archaeobotanical work with a larger sample size can clarify the trends observed in this study.

4.7 References

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Chapter 5: **Conclusion**

5.1 Overview

During the 3rd - 2nd millennium BCE, the Eurasian landmass was at the height of a post-domestication dispersal of crops, livestock, and technologies across markedly different environments. This deep historical process, often referred to as food globalization in prehistory or trans-Eurasian exchanges, paved the way for an interconnected Eurasian techno-economic system (Jones et al., 2016b; Liu et al., 2019). The translocation brought new domesticated plants and animals, notably wheat, barley, broomcorn and foxtail millet, and sheep, goats, horses, cattle, and pigs, into novel environments and cultural spheres that were distinct from those of their centers of origin.

Of particular interest to this dissertation are the distinct culinary and social-technological systems rooted in East and Southwest Asian traditions. In East Asia, boiling and steaming whole grains is closely related to commensality and ritually charged practices involving ancestral worshipping (Fuller and Rowlands, 2011). Such a cooking system likely drove preferences toward smaller and sticky grains, such as millets and rice, for cooking efficiency (Fuller and Rowlands, 2011; Liu et al., 2016a).. In southwest Asia, different culinary practices and animal management were developed. Grains were ground into flours for roasting and baking into early forms of bread (Fuller and Rowlands, 2011).

These differences encourage contemplation on what occurs when plants (and animals) domesticated in distinctly different cultural-environmental systems are adopted by another

community and incorporated into new social norms. This dissertation tackles such questions concerning the context in which agropastoral innovation emerges in history. I engage with the recent scholarly discussion on the socio-cultural ramifications of prehistoric globalization, including how novel food products were transformed in deep-seated indigenous management and in the case of the Tibetan case study (Chapter 4), culinary regimes. Culinary systems served as a major filter in the adaptation of newly introduced grains or their rejection (Liu et al., 2016a; Ritchey et al., 2022; Sun et al., 2024) while some livestock were folded into indigenous management systems while others were not (Vaiglova et al., 2021; Zhang et al., 2024). The adoption, modification, and/or rejection of grains, livestock, and their associated management systems has implications for understanding broader anthropological processes of cultural exchange, foodways, stability, labor organization, and institutional maintenance (Sahlins, 1976; Goody, 1982; Netting, 1986; Sherratt, 1995; Douglas, 2003; Frachetti, 2012).

Rather than investigating the *Fields on the Hoof*, as coined by Robert Ekvall (1968) in his ethnography on high-altitude Tibetan pastoralism, in this dissertation I instead turn the attention to the less studied aspect of pastoral lifeways – the agriculture, or the fields *under* the hoof– to highlight the necessary negotiations made by these agropastoral communities. In particular, I set out to characterize time and labor investment into cultivation by using carbon and nitrogen isotope compositions measured from charred grains – wheat, barley, broomcorn and foxtail millet, and peas – as proxies for watering and manuring strategies, respectively. I apply theories of intensification to assess labor investment into cultivation (Boserup, 1965; Halstead, 1989, 1990; Halstead and O’Shea, 1989). The trends observed at each study site, located in distinct environments, show considerable complexities in how localized decisions were both constructed within and pushed the boundaries of existing strategies, which helped facilitate the long-distance

dispersals across the Inner Asia mountains, transforming Eurasian history. In the following sections, I summarize the key findings of each data chapter and discuss the broader implications and future directions of this research.

5.2 Summary of Dissertation Chapters

5.1.1 Chapter 2

In Chapter 2, I examined the labor investments in wheat and barley cultivation by agropastoralists at the highland site of Chap, in the Kochkor Valley of the Tien Shen mountains, Kyrgyzstan. Giedre Motuzaite-Matuzeviciute and colleagues conducted excavations at the location and provided access to the macrobotanical remains and relevant data for analysis (Motuzaite-Matuzeviciute et al., 2019b, 2020, 2021a, 2021b). I selected the macrobotanical remains and performed the stable isotope analysis and subsequent data processing. The chapter received input from co-authors of the journal article Giedre Motuzaite-Matuzevic and Xinyi Liu. I am preparing this chapter for submission to Nature: Scientific Reports or Journal of Archaeological Sciences.

The Chap site presents an interesting case study for understanding the Bronze to Final Bronze Age transition in the IAMC, with its early evidence of wheat, barley and millet cultivation during the Bronze Age occupation of Chap II (2474-2162 cal. BCE), and a later transition to a more complex cultivation system with the addition of legumes during the Chap I occupation (1102-816 cal. BCE) (Motuzaite-Matuzeviciute et al., 2019b, 2020, 2021b). During the 3rd millennium BCE, isotopic evidence indicates livestock foddering or grazing on C₄ plants and direct human consumption of millets in the region around Chap (Motuzaite-Matuzeviciute et

al., 2022a). An increase in nitrogen levels through time of the human populations from Bronze, Iron Age and Medieval/Turkic populations were interpreted as suggesting a transition from a cereal-based economy to a more animal based subsistence, potentially indicating growing pastoral lifeways (Motuzaite-Matuzeviciute et al., 2022a). Further, zooarchaeological analyses indicate a selection for sheep for wool production, in addition to the presence of horse, cattle, and goats at Chap (Ananyevskaya et al., 2021).

My stable isotope analysis of the wheat and barley grains from Chap reveals a general trend of increasing investment in watering and manuring, as indicated by the increasing $\Delta^{13}\text{C}_{\text{plant-air}}$ and $\delta^{15}\text{N}$ values through time. The evidence for increased water availability through time was more pronounced in the wheat remains, while barley exhibited more isotopically pronounced soil improvement through time. Overall, wheat has more water available than barley, while barley has generally higher nitrogen levels, suggesting more anthropogenic manuring or cultivation in more arid, open soils and/or previously uncultivated highland pastures with higher relative nitrogen than exhausted farmstead cultivation plots. A comparison of the habitats of wild taxa recovered from Chap with the $\Delta^{13}\text{C}_{\text{plant-air}}$ values of the crops show complimentary evidence of wetter cultivation systems through time. The signatures for abundant water availability, particularly in wheat and, to a lesser extent in barley, indicate in the semi-arid environment that Chap is situated in that the Bronze Age agropastoralists invested in water management systems to ensure the success of their crops. Remnants of these or later systems are present in the landscape today (Rouse et al., 2022). The Chap agropastoralists negotiated the needs of livestock herding, specialized wool production and seasonal mobility (Hermes et al., 2019, 2022; Ananyevskaya et al., 2021) with those of fairly intensive plant cultivation to succeed above 2000 masl.

The increase $\delta^{15}\text{N}$ values through time has implications for understanding the overall paleodietary reconstructions. Hermes et al. (2019) hypothesis that the increase in $\delta^{15}\text{N}$ values seen in human remains is the result a transition to a more pastoralist subsistence strategy relying on more meat and dairy-based products. With the new evidence of increasing nitrogen values in the crops, the trends seen in the human isotopes can be, at least in part, attributed to more intensive agricultural production, at least from the Broze to Final Bronze Age transition captured in my study. Instead of increasing nomadic pastoralism, potentially we see increasing investment in plant cultivation and a transition to a more sedentary production economy by at least some of the population.

5.1.2 Chapter 3

In Chapter 3, I present the results of macrobotanical and stable isotope analysis of the cultivation system at the multi-period site of Tasbas (1500 masl), in the Dzhungar Mountains of Semirech'ye, Kazakhstan. I led the flotation sampling and processing during the 2023 field season and conducted macrobotanical analysis on the assemblage in 2024. I combined this data with previously analyzed macrobotanical remains from the 2011 field season conducted by Robert Spengler for his 2013 dissertation (Spengler, 2013). I selected and processed crop remains and wild taxa for stable isotope analysis from both the 2011 and 2023 seasons. I performed calculations, data processing, and writing, with input from article co-authors Pala Doumani Dupuy, Xinyi Liu, and Michael Frachetti. I will prepare this chapter for submission for publication with Journal of Archaeological Sciences or Antiquity.

The occupation of Tasbas spans the Early Bronze Age to historic Kazakh periods, with evidence for seasonal and semi-permanent occupation utilizing an agropastoral production

system. Evidence for domesticated free-threshing wheat are first present in a cremation cyst in small numbers dated to 2631 – 2562 cal. BCE. This seems to be a shared cultural practice, as a similar, even earlier (2650 cal. BCE) cremation context was recovered from the neighboring site of Begash (Frachetti et al., 2010). From the Middle Bronze to Iron Age deposits, there is evidence for local cultivation of domesticated crops, now including naked and hulled barley, foxtail millet, and peas in addition to wheat and broomcorn millet.

The 2023 excavation bolsters the previous archaeobotanical analyses and provides new evidence for confirming the identification of the wheat at Tasbas as free-threshing wheat, *Triticum aestivum*, as evidenced by abundant remains of identifiable rachis remains from the Late Bronze Age deposits. The stable isotope data investigates further the cultivation practices of the crop assemblage. I analyzed wheat and barley grains from across the occupation, however limited by seed abundance for some periods. Overall, the crops received adequate to abundant water, with wheat increasing through time. Nitrogen values are also generally over the natural baselevel but decrease over time, suggesting an extensification trend in manuring practices. Peas were well-watered and well-manured, as indicated by their high $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. Conservative sampling of the peas limits a diachronic analysis. The wild taxa, both isotopically and ecologically, provide a comparable dataset that highlights the changing cultivation and/or ecological systems at Tasbas.

Additionally, the combined 2011 and 2023 macrobotanical remains show diachronic changes in the crop systems, with the introduction of peas in the Middle Bronze Age and growing reliance on naked barley by the Late Bronze Age. Overall, the data show the complex multi-cropping system with invested labor for wheat, barley, pea, and millet production at

Tasbas, likely made possible by the semi-nomadic, potentially year-round occupation of the site by agropastoralists.

5.1.3 Chapter 4

In Chapter 4, I present the results of a stable isotope analysis of barley remains from the Western Tibetan sites of Piyang, Dingdong, and Jiweng, which are a part of the Piyang-Dongga complex. This paper was published in *Frontiers in Environmental Archaeology* in August of 2024. Data was provided by Hongliang Lu and Tang Li. I performed the laboratory and data analyses with the assistance of Petra Vaiglova and Yufeng Sun. I prepared the manuscript, with edits from co-authors, Hongliang Lu, Tang Li, Petra Vaiglova, Yufeng Sun, Xinyi Liu, and Michael Frachetti. I have obtained written permission from all co-authors to include a pre-print version of this open-access manuscript as a chapter in this dissertation.

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from Piyang, Dingdong, and Jiweng show intensive management of barley above 4000 masl. The barley grains had optimal to superfluous water availability, which, in the semi-arid to arid Western Plateau, would have required water management and planning through small-scale irrigation, hand watering, and/or optimizing natural wetter areas. The grains had very high $\delta^{15}\text{N}$ values; some of the highest values I have seen in archaeological crop remains. While natural factors from the soil aridity and abundance of soil N on the Tibetan Plateau likely contribute to these $\delta^{15}\text{N}$ values, anthropogenic manuring and soil enrichment likely drives the observed trends. At such a high altitude and environment, this intensive cultivation system was possibly required for successful barley cultivation. However, my results from other sites on the Tibetan Plateau, discussed below, suggest this may be a unique Western Tibetan system, not a shared Tibetan practice. I also proposed a method to gauge the

role of cultivation versus culinary systems in the selection for grain sizes. The limited dataset hinders concrete conclusions, but further work, see below, will tease out these trends.

5.2 Broader Implications and Future Directions

5.2.1 Impact of paleodietary reconstructions

Stable isotope values of animal and human remains provide immense information regarding paleodiets, and many researchers use $\delta^{15}\text{N}$ values of herbivorous as a baselevel for trophic estimate. However, without assessing the nitrogen isotope composition in soil and plants, our understanding of the complex food systems in the past is incomplete. My analysis of the $\delta^{15}\text{N}$ values of plant remains from the IAMC and Tibetan Plateau provides critical data for interpreting past, current, and future paleodietary reconstructions from human and animal remains. For example, humans from the Early Bronze Age to Medieval Age Kyrgyzstan show increasing $\delta^{15}\text{N}$ through time, which is interpreted as reflecting a shift towards greater reliance on animal products and growing nomadic pastoralism (Motuzaite-Matuzeviciute et al., 2022a). However, the results from the Chap wheat and barley show these also increased in $\delta^{15}\text{N}$ through time. At least some of the changes in the human $\delta^{15}\text{N}$ values can be attributed to intensifying agricultural practices, particularly increased manuring. Similarly, the variation seen in $\delta^{15}\text{N}$ of livestock from Dali, Tasbas, and Begash in Kazakhstan (Hermes et al., 2019) can be further enlightened by consumption of elevated, but also diachronically decreasing, $\delta^{15}\text{N}$ values of barley and wheat from Tasbas.

In addition, I present novel attempts at complementing crop isotope values with the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wild taxa, primarily arable weeds. Future work fleshing out intra-species

variation in isotopic values, establishing taxa-specific thresholds, and increased sampling will likely improve this method for characterizing the agricultural landscape. Additionally, in an agropastoral context, this method may aid in discerning wild taxa that are byproducts of crop processing (and grew in the field) from taxa that were consumed by livestock and deposited through dung burning for fuel. The very nature of agropastoral systems – such that macrobotanical remains can enter the archaeological record from both direct human consumption activities and the use of livestock dung as fuel – is the likely cause for the sometimes-ambiguous isotopic results of the wild taxa. Further research incorporating these distinct datasets and expanding analysis of plant stable isotopes across the broader IAMC and surrounding regions could complicate traditional understandings of pastoralism signatures in paleodietary reconstructions and inform a more comprehensive understanding of these production systems.

5.2.2 Cuisines or cultivation?

Domestication of cereal crops occurred within distinct cuisines and associated cooking techniques that selected for particular traits suited to each culinary tradition (Sakamoto, 1996; Fuller and Rowlands, 2009, 2011). The spread of domesticates across Eurasia brought these crops out of their deep-seated cuisines and into new environments and cultural settings with their own labor organization and food preparation traditions. The selective pressures of these new cuisines modified certain traits captured within the grains themselves. For example, when wheat and barley moved out of the Southwest Asian culinary system of grinding and baking and into ancient China, it was folded into the East Asian tradition of whole grain boiling and steaming. Selective pressures for smaller grains drove a dramatic decrease in grain size of these new cereal crops (Liu et al., 2016a; Ritchey et al., 2022). When the East Asian broomcorn and foxtail millets moved westward into Inner Asia and beyond, these small seeded grains domesticated

within the boiling and steaming traditions of ancient China substantially increased in grain size when they encountered new baking and grinding traditions in the West (Sun et al., 2024). Alternative hypotheses for the grain size trends seen across Eurasia include adaptations to new, harsher environments (Motuzaite-Matuzeviciute et al., 2021a) and the effects of growing conditions, including manuring, watering, temperature, row spacing, and weeding (Savin and Nicolas, 1996; Poltoreskyi et al., 2019; van Bommel et al., 2021; Larsson and Bergman, 2023b; Palchetti et al., 2023). By comparing the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of cereal grains as proxies for watering and manuring practices to grain size, I can evaluate this latter hypothesis that increased investment in growing conditions produced higher yield through larger grain size. I initiated this analysis in Chapter 4 with the barley grains from Western Tibet, but small sample size hindered definite conclusions. Future research with larger sample sizes in this area would be helpful in exploring this line of research.

5.2.3 Localization of agricultural systems

When crops and livestock spread across Eurasia from their respective domestication centers did their associated management technologies travel with them? Evidence from Europe indicates that agricultural “packages” of crops and livestock spread through Europe, with various local manifestations of same basic intensive agricultural system adopted into novel socio-cultural and environmental landscapes (Bogaard, 2004, 2005; Halstead, 2006; Treasure et al., 2019).

Interestingly, when new types of domesticated livestock, sheep/goats and cattle, were introduced into the Hexi Corridor, where communities already managed domestic pig, a different pattern emerges. While cattle were folded into a close and intensive management system similar to that of pigs, sheep/goats were extensively managed, similar to some of their agropastoralist neighbors

in the IAMC and Southwest Asian farmers who were the source of these new livestock (Vaiglova et al., 2021).

The research I have presented in this dissertation engages with this anthropological question in its assessment of the cultivation strategies of essential communities for the trans-Eurasian spread of domesticated crops. Similar to the situation in Neolithic Europe, the communities I have analyzed did not have any domesticated crops prior to their introduction to the region. In other words, our current understanding indicates no local domestication centers in the mountains of Inner Asia at the time of introduction of domesticated wheat, barley, and legumes from Southwest Asia and millets from East Asia. The signatures of intensive cultivation strategies, whilst variable dependent on taxa and chronological trends at each of the sites analyzed, suggest a similar trend to that of Neolithic Europe (Bogaard, 2005). Each agropastoral community in the broader IAMC developed their own cultivation strategies to meet their own needs. Knowledge of intensive cultivation techniques may have travelled with the crops on their transcontinental journeys but were clearly adjusted and modified to fit an agropastoral lifestyle in the mountains of Inner Asia. In addition to the analyses of the crop assemblages at Chap, Tasbas, and those of the Piyang Dongga complex, I conducted macrobotanical analysis of remains from the site of Koken in northeastern Kazakhstan and stable isotope analyses of barley grains and wild taxa from the Tibetan Plateau sites of Kaerdong and Bangga (Figure 1). The results from these analyses further enforce the localization of cultivation practices, or lack of cultivation completely, across the broader IAMC.

Kaerdong and Bangga are two additional Tibetan Plateau agropastoral sites that show evidence of domesticated crop cultivation between the Bronze and Iron Ages. Kaerdong (4300 masl) is located roughly 115 km southeast of the Piyang Dongga complex in Gar County, Ngari

Prefecture, western Tibetan Plateau and dates between the 5th and 8th century CE. Archaeological evidence shows a mixed strategy of agropastoralism, hunting, fishing, and foraging (Song et al., 2018). Macrobotanical analyses provide clear evidence for local cultivation of naked and hulled barley and possible evidence of wheat and Tatar buckwheat (*Fagopyrum tataricum*). Song et al. (2018) also identify the presence of one rice (*Oryza sativa*) fragment and nine rice spikelets. Due to the growing requirements of rice, the researchers argue that the crops presence is the result of trade with rice farmers at lower and warmer altitudes. I conducted plant stable isotope analysis on 10 barley grains from contexts 3,4, 5, and 6, which date to CE 600-700. Bangga (ca. 1055 BCE – CE 2104, 3750 masl) is located in the central Tibetan Plateau, near the capital city of Lhasa. Archaeological excavations and subsequent analyses reveal an intensive agropastoral system, including water and fodder provisioning, corralling, and specialized culling of sheep and goats for milk production (Zhang et al., 2022, 2024). Similar to Kaerdong, barley was the primary cultivar, with small numbers of wheat and buckwheat present. I conducted plant stable isotope analyses on 24 barley grains, from contexts F1 and F4, dated to 750-400 BCE.

Results from Bangga and Kaerdong (Supplementary Table 23), along with the other Tibetan sites discussed in Chapter 4, are presented in Supplementary Figure 17. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from Kaerdong align closely with those of the other western Tibetan sites of Piyang, Dingdong, and Jiweng, albeit occupied centuries later. The barley has similarly high $\delta^{15}\text{N}$ values, well above the local natural baselevel, indicating intensive manuring of the crop. The mean $\delta^{13}\text{C}$ value is above the SWT and overall, the grains look similar to the site of Jiweng. Interestingly, Bangga, occupied prior to the earliest site from the western Tibet sample, has a distinctly different barley isotopic signature. While the mean $\delta^{13}\text{C}$ value is the highest of all the Tibetan sites, the mean $\delta^{15}\text{N}$ value is the lowest. Most of the barley grains are above the natural

baselevel, but do not exhibit the extremeness of the western Tibetan barley; the Bangga grains are much more aligned with values from Chap and Tasbas and other “intensive” agricultural systems in Eurasia.

Koken (360 masl) lies in the arid steppe zone of northeastern Kazakhstan, near the present-day city of Semey. The region today receives 375 mm of annual rainfall. A burial complex and occupation site are divided by seasonal rivers that create a wetter and greener oasis amidst the arid grassland and nearby Kokentau Mountains (800 masl). This site, with evidence of the earliest human burial in Kazakhstan from the mid-6th millennium BCE (Doumani Dupuy et al., 2023), contains pastoralist occupation layers that continue until the historic and modern periods, with abundant Bronze Age deposits and structures.

I analyzed flotation samples from Koken, in the hopes of recovering potential evidence for a northwestern route of East Asian millets and potentially other domesticated grains across the Kazakh steppe. However, no remnants of domesticated crops were found. In fact, the deposits were relatively sparse in macrobotanical remains and the seeds that were recovered present a picture of the pastoralist activities at the site. I will report here on the samples from domestic contexts, but burial deposits were also analyzed and included in the full report in Supplementary Table 22. The domestic assemblages, while sparse and containing only 278 charred seeds from 52 flotation samples, are dominated by *Chenopodium* spp. and *Cheno/Ams*, making up 93.3% of the assemblage. Most taxa identified are summer annuals or perennials, with fruiting periods from June to September, suggesting that Koken was primarily utilized during the summer to fall. A habitat analysis of the taxa indicates mostly ruderal and moist-soil or wetland plants present, with a few grassland/steppe taxa (Appendix 9, Supplementary Figure 16). This reflects quite well the surrounding landscape around the site today – a rich moist

meadow between two seasonal rivers that are home to small shrubs, forbs, herbs, and trees, particularly along the riverbanks (Supplementary Figure 18). Future work on the charcoal remains could provide additional information of the paleoclimate and resource use of these pastoralists.

The Koken assemblage resonates with that of the famous horse-domestication site of Botai in western Kazakhstan (Motuzaite-Matuzeviciute et al., 2019a), where an absence of domesticated crops and sparse recovery characterizes the pastoralist nature of the site. There is also a lack of millet husks in ceramics from Koken, while present in ceramics from IAMC sites (Endo et al., 2023). There is evidence, however, of interaction between the communities at Koken and the broader Eurasian Steppe and IAMC (Doumani Dupuy et al., 2021b, 2021a), which implies that the pastoralists at Koken knew of cultivation conducted by neighbors occupying the mountains and foothills, but chose not to engage in the practice. Instead, they emphasized a hunting and pastoral subsistence, utilizing the oasis-like environment surrounding Koken amidst the broader arid steppe landscape.

The localization of agropastoral strategies, in particular the cultivation systems I analyzed and livestock management as explored in the Hexi Corridor by Vaiglova et al. (2021) and in the Tibetan Plateau by Zhang et al. (2024), resonates with Robert Netting's statement on ingenuity of communities:

“Students of civilization have often credited the development of intensive agriculture to revolutionary inventions such as metal tools, the plow, and domesticated draft animal ... or to particular environments which challenged the creative powers of the inhabitants ... Comparative evidence now suggests that a great many peoples practice intensive

cultivation with rudimentary tools, and that the necessary knowledge need not be diffused from a few centers of cultural innovation but may be developed to meet localized needs.”

(Netting, 1986, p. 67)

Indeed, we see various local permutations of agropastoral systems that, while the crops and animals were introduced from neighboring regions, the technologies regarding their management did not necessarily come hand-in-hand. Each community adopted what they found useful and necessary, learning strategies from neighbors and newcomers alike, and invented their own ways to successfully incorporate crops and livestock herding into semi-nomadic lifestyles in the mountains of Inner Asia. This shared knowledge of cultivation and the localization of community practices echoes with the ceramic traditions in the IAMC. The ceramic assemblages from the IAMC exhibit a broader trend of long-standing ceramic traditions that still contained local variation in paste, sourcing, and decoration, reflecting the different scales of interactions that influenced the knowledge behind pottery production (Doumani, 2014; Doumani Dupuy et al., 2019). Recent genetic work aligns, showing that the diachronic and geographic variations seen in both subsistence and ceramics at the IAMC sites, are not the result of distinct population migrations, but rather the slow processes of integration of new populations, likely through intra-community marriages and interaction (Narasimhan et al., 2019).

On the Tibetan Plateau, the differences in cultivation strategies exhibited by the western Tibetan sites and the central Tibetan site also align with other lines of evidence outlining social interaction. Models of Bronze and Iron Age material and cultural networks across the Plateau show complex interactions between central and eastern Tibet, with distant connections with western Tibetan communities (Chen et al., 2024). Further, genetic data shows a nearly identical interaction sphere for the central and eastern regions, while the west remains relatively isolated

prior to 2500 BP (Wang et al., 2023). The agropastoral communities were connected by their shared practices through networks of interaction, but developed distinct local traditions based on their social systems. Stable isotope analysis of crop remains from sedentary farming sites in broader study areas presented in this dissertation, such as Sarazm in northwestern Tajikistan (4th-3rd millennium BCE) (Spengler and Willcox, 2013) and Qasim Bagh, Kanispur, and neighboring sites in the Kashmir, India (3rd millennium BCE) (Spate et al., 2017; Pokharia et al., 2018; Betts et al., 2019), would provide a comparative dataset for differences and similarities between agropastoral cultivation systems and sedentary farmers. Further stable isotope research on plant remains from other agropastoral sites in the mountains of Inner Asia and other locations along the prehistoric globalization routes will broaden our understanding of these processes.

5.3 References

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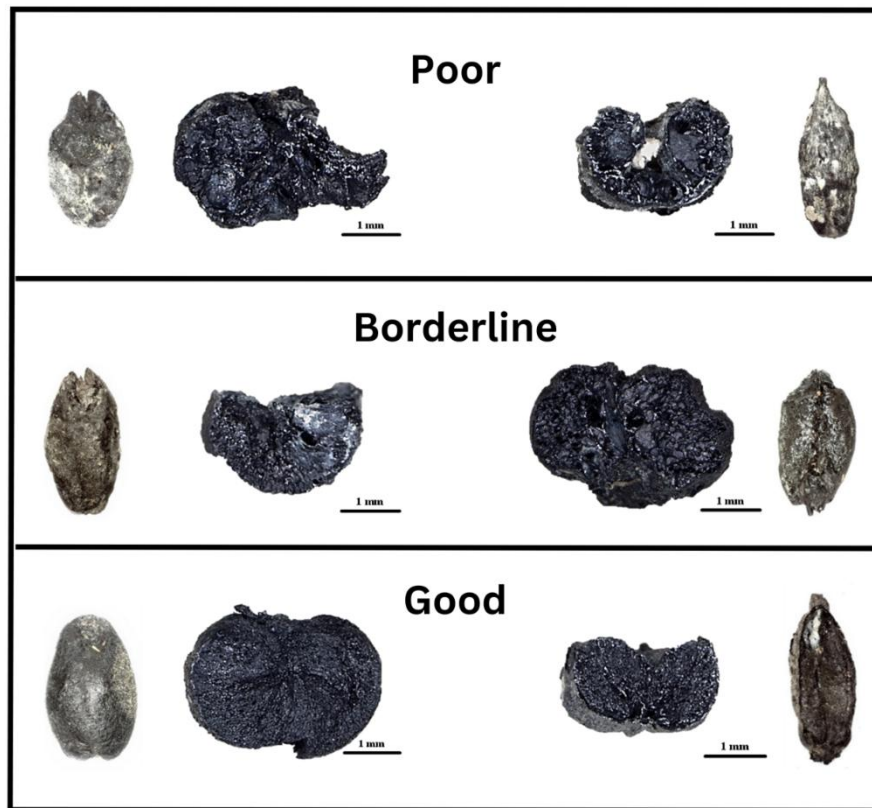
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Appendices

Appendix 1.



Supplementary Figure 1. Examples of preservation charring categories: poor, borderline, and good. Images of all grains analyzed are available in Washington University in St. Louis Open Scholarship Institutional Repository, available at <https://doi.org/10.7936/6RXS-108275>.

Appendix 2. Chapter 2 Supplementary Tables

Supplementary Table 1. $\delta^{15}\text{N}$ of select herbivores from Motuzaite Matuzeviciute (2022) from sites Chap I and II, Kara-Tumshuk, Kok-Sai, Kok-Tash, and Aigyrzhal 2, with summarized calculations for developing the natural vegetation baselevel.

$\delta^{15}\text{N}$ results of herbivores with values below 7 ‰					
Lab number	Site	Species	Dating	$\delta^{15}\text{N}$ ‰	N‰
BTC-KY-F3	Kara-Tumshuk	Horse	Early-Late BA (2500–1200 BC)	4.19	30.6
BTC-KY-F19	Aigyrzhal 2	Wild goat	Early-Late BA (2500–1200 BC)	4.9	16
BTC-KY-F89	Chap II	Horse	Early-Late BA (2500–1200 BC)	5.43	14.39
BTC-KY-F61	Kok-Tash	Horse	Turkic-medieval (200 BC–AD 1700)	5.62	13.16
BTC-KY-F46	Chap II	Ovis	Early-Late BA (2500–1200 BC)	5.78	41.74
BTC-KY-F46	Chap II	Ovis	Early-Late BA (2500–1200 BC)	5.78	41.74
BTC-KY-F62	Kok-Tash	Horse	Turkic-medieval (200 BC–AD 1700)	5.89	16.34
BTC-KY-F36	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.57	43.66
BTC-KY-F94	Chap II	Sheep	Early-Late BA (2500–1200 BC)	6.57	5.3
BTC-KY-F72	Kok-Sai	Caprine	Turkic-medieval (200 BC–AD 1700)	6.62	33.91
BTC-KY-F76	Chap I	Caprine	Final BA/EIA (1200–200 BC)	6.66	19.01
BTC-KY-F1	Kara-Tumshuk	Caprine	Early-Late BA (2500–1200 BC)	6.69	42.24
BTC-KY-F75	Chap I	Caprine	Final BA/EIA (1200–200 BC)	6.77	20.51
BTC-KY-F44	Chap II	Ovis	Early-Late BA (2500–1200 BC)	6.93	46.2
BTC-KY-F41	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.97	38.37
BTC-KY-F48	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.98	44.58
BTC-KY-F84	Chap II	Sheep	Early-Late BA (2500–1200 BC)	6.98	14.49
BTC-KY-F37	Chap II	Ovis	Early-Late BA (2500–1200 BC)	6.99	45.24
BTC-KY-F50	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.99	43.6
Average $\delta^{15}\text{N}$ ‰				6.3	
Average $\delta^{15}\text{N}$ ‰ - 3 ‰				3.3	
Average $\delta^{15}\text{N}$ ‰ - 5 ‰				1.3	
Approximate natural vegetation baselevel				1.3 - 3.3	
$\delta^{15}\text{N}$ results of all herbivores					
Lab number	Site	Species	Dating	$\delta^{15}\text{N}$ ‰	N‰
BTC-KY-F3	Kara-Tumshuk	Horse	Early-Late BA (2500–1200 BC)	4.19	30.6
BTC-KY-F19	Aigyrzhal 2	Wild goat	Early-Late BA (2500–1200 BC)	4.9	16
BTC-KY-F89	Chap II	Horse	Early-Late BA (2500–1200 BC)	5.43	14.39
BTC-KY-F61	Kok-Tash	Horse	Turkic-medieval (200 BC–AD 1700)	5.62	13.16
BTC-KY-F46	Chap II	Ovis	Early-Late BA (2500–1200 BC)	5.78	41.74
BTC-KY-F46	Chap II	Ovis	Early-Late BA (2500–1200 BC)	5.78	41.74
BTC-KY-F62	Kok-Tash	Horse	Turkic-medieval (200 BC–AD 1700)	5.89	16.34
BTC-KY-F36	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.57	43.66
BTC-KY-F94	Chap II	Sheep	Early-Late BA (2500–1200 BC)	6.57	5.3
BTC-KY-F72	Kok-Sai	Caprine	Turkic-medieval (200 BC–AD 1700)	6.62	33.91
BTC-KY-F76	Chap I	Caprine	Final BA/EIA (1200–200 BC)	6.66	19.01
BTC-KY-F1	Kara-Tumshuk	Caprine	Early-Late BA (2500–1200 BC)	6.69	42.24
BTC-KY-F75	Chap I	Caprine	Final BA/EIA (1200–200 BC)	6.77	20.51
BTC-KY-F44	Chap II	Ovis	Early-Late BA (2500–1200 BC)	6.93	46.2
BTC-KY-F41	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.97	38.37
BTC-KY-F48	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.98	44.58
BTC-KY-F84	Chap II	Sheep	Early-Late BA (2500–1200 BC)	6.98	14.49
BTC-KY-F37	Chap II	Ovis	Early-Late BA (2500–1200 BC)	6.99	45.24
BTC-KY-F50	Chap II	Bos	Early-Late BA (2500–1200 BC)	6.99	43.6
BTC-KY-F39	Chap II	Bos	Early-Late BA (2500–1200 BC)	7	39.14
BTC-KY-F92	Chap II	Sheep	Early-Late BA (2500–1200 BC)	7.15	15.38

Supplementary Table 1. Continued (page 2 of 2)

BTC-KY-F4	Kara-Tumshuk	Caprine	Early-Late BA (2500–1200 BC)	7.19	34.82
BTC-KY-F74	Chap I	Caprine	Final BA/EIA (1200–200 BC)	7.21	16.22
BTC-KY-F35	Chap II	Bos	Early-Late BA (2500–1200 BC)	7.22	43.5
BTC-KY-F49	Chap II	Bos	Early-Late BA (2500–1200 BC)	7.28	32.23
BTC-KY-F90	Chap II	Cattle	Early-Late BA (2500–1200 BC)	7.41	14.71
BTC-KY-F63	Kok-Tash	Caprine	Turkic-medieval (200 BC–AD 1700)	7.49	18.73
BTC-KY-F91	Chap II	Sheep	Early-Late BA (2500–1200 BC)	7.51	15.85
BTC-KY-F47	Chap II	Bos	Early-Late BA (2500–1200 BC)	7.53	41.12
BTC-KY-F73	Chap I	Caprine	Final BA/EIA (1200–200 BC)	7.53	19.07
BTC-KY-F40	Chap II	Ovis	Early-Late BA (2500–1200 BC)	7.66	44.68
BTC-KY-F42	Chap II	Bos	Early-Late BA (2500–1200 BC)	7.69	39.17
BTC-KY-F78	Chap I	Cattle	Final BA/EIA (1200–200 BC)	7.7	17.12
BTC-KY-F66	Kok-Sai	Cattle	Turkic-medieval (200 BC–AD 1700)	7.74	41.16
BTC-KY-F45	Chap II	Bos	Early-Late BA (2500–1200 BC)	7.78	39.15
BTC-KY-F2	Kara-Tumshuk	cf. Horse	Early-Late BA (2500–1200 BC)	7.82	35.35
BTC-KY-F77	Chap I	Caprine	Final BA/EIA (1200–200 BC)	8.02	13.82
BTC-KY-F80	Chap II	cf. Cattle	Early-Late BA (2500–1200 BC)	8.07	14.33
BTC-KY-F51	Chap II	Bos	Early-Late BA (2500–1200 BC)	8.08	37.8
BTC-KY-F43	Chap II	Ovis	Early-Late BA (2500–1200 BC)	8.11	38.13
BTC-KY-F81	Chap II	Cattle	Early-Late BA (2500–1200 BC)	8.22	15.03
BTC-KY-F93	Chap II	Sheep	Early-Late BA (2500–1200 BC)	8.24	14.45
BTC-KY-F85	Chap II	cf. Cattle	Early-Late BA (2500–1200 BC)	8.3	13.17
BTC-KY-F34	Chap II	Capra	Early-Late BA (2500–1200 BC)	8.38	41.26
BTC-KY-F38	Chap II	Bos	Early-Late BA (2500–1200 BC)	8.66	46.08
BTC-KY-F88	Chap II	Sheep	Early-Late BA (2500–1200 BC)	9.24	14.54
BTC-KY-F83	Chap II	cf. Cattle	Early-Late BA (2500–1200 BC)	9.72	15.53
BTC-KY-F82	Chap II	Animal	Early-Late BA (2500–1200 BC)	9.73	10.44
BTC-KY-F86	Chap II	Sheep	Early-Late BA (2500–1200 BC)	9.74	14.87
BTC-KY-F87	Chap II	Sheep	Early-Late BA (2500–1200 BC)	10.63	15.14
BTC-KY-F70	Kok-Sai	Caprine	Turkic-medieval (200 BC–AD 1700)	10.99	27.2
BTC-KY-F5	Kara-Tumshuk	Caprine	Early-Late BA (2500–1200 BC)	11.23	36.45
BTC-KY-F79	Chap I	Caprine	Final BA/EIA (1200–200 BC)	11.92	36.42
Average $\delta^{15}\text{N}\text{‰}$				7.6	
Average $\delta^{15}\text{N}\text{‰}$ - 3 ‰				4.6	
Average $\delta^{15}\text{N}\text{‰}$ - 5 ‰				2.6	
Approximate natural vegetation baselevel				2.6 - 4.6	

Supplementary Table 2. Analysis of confidence intervals and independent group contrasts, displayed in Supplementary Figure 2, between qualitatively assigned charring status and $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wheat and barley grains.

Mean Difference					
Outcome variable	Charring status	M	95% CI		n
			LL	UL	
$\Delta^{13}\text{C}$	good	17.5	17.3	17.8	62
	borderline	17.4	17.1	17.7	51
	poor	17.5	17.3	17.8	102
$\delta^{15}\text{N}$	good	6.1	5.6	6.6	62
	borderline	6.1	5.5	6.6	51
	poor	5.7	5.3	6.1	102
	(borderline and good)	6.1	5.7	6.5	
	poor – (borderline and good)	-0.4	-0.9	0.2	
Note. Variances are assumed equal, so s_p was used to calculate each CI.					

Supplementary Table 3. Results of stable isotope analysis of Chap I and II domesticated taxa and wild taxa (Page 1 of 11).

LAB ID	Site	context	Taxa	Length	Breadth	Thickness	L:B	status	Count	d13c	%C	d15n	%N	C:N	$\Delta^{13}C$
CH1_1_H1	Chap I	F18_bag 47, sq, c4	Naked Hordeum	5.33	2.94	2.59	1.81	poor	1	-23.98	64.16434	6.179149	1.508265	49.63212	17.90949
CH1_1_H2	Chap I	F18_bag 47, sq, c4	Naked Hordeum	4.87	2.46	1.87	1.98	poor	1	-21.6973	60.68953	7.438604	3.278624	21.59578	15.53436
CH1_1_H3	Chap I	F18_bag 47, sq, c4	Naked Hordeum	5.2	2.64	1.95	1.97	good	1	-22.0161	63.73915	6.627157	1.67201	44.47481	15.85642
CH1_1_H4	Chap I	F18_bag 47, sq, c4	Naked Hordeum	4.52	2.53	2.05	1.79	poor	1	-23.1675	61.04842	7.632908	2.924262	24.35595	17.06278
CH1_1_H5	Chap I	F18_bag 47, sq, c4	Naked Hordeum	5.24	2.68	1.97	1.96	borderline	1	-25.68	61.245	5.77	2.7	22.32	19.68552
CH1_1_T1	Chap I	F18_bag 47, sq, c4	Triticum	4.06	3.26	2.8	1.25	poor	1	-23.5213	56.78126	9.23466	2.844551	23.28832	17.43128
CH1_1_T2	Chap I	F18_bag 47, sq, c4	Triticum	4.51	2.37	1.82	1.9	poor	1	-22.9546	58.85895	6.507352	2.216846	30.97589	16.84118
CH1_1_T4	Chap I	F18_bag 47, sq, c4	Triticum	3.4	2.82	2.53	1.21	borderline	1	-23.1345	62.38901	6.879853	3.77529	19.27989	17.02844
CH1_1_T5	Chap I	F18_bag 47, sq, c4	Triticum	5.49	3.92	2.8	1.4	poor	1	-23.8191	67.43042	4.154559	2.22045	35.42922	17.7417
CH1_1_T6	Chap I	F18_bag 47, sq, c4	Triticum		3.01	2.1		good	1	-27.27	60.209	6.9	3.8	15.96	21.35228
CH1_10_H1	Chap I	f18 49, square 4	Naked Hordeum	4.8	2.27	1.76	2.11	good	1	-23.79	58.21	8.36	3.14	18.51	17.71135
CH1_10_H2	Chap I	f18 49, square 4	Naked Hordeum	4.43	2.67	1.89	1.66	good	1	-23.61	57.414	6.04	4.4	13.01	17.52374
CH1_10_H3	Chap I	f18 49, square 4	Naked Hordeum	5.32	3.25	2.18	1.64	poor	1	-22.2	63.995	4.46	2.9	21.89	16.05645
CH1_10_T1	Chap I	f18 49, square 4	Triticum	3.79	3.17	2.78	1.2	borderline	1	-22.05	55.29	4.91	3.54	15.63	15.90061
CH1_11_T1	Chap I	F18, 34	Triticum	3.69	3.07	2.24	1.2	good	1	-22.95	62.359	4.8	2.9	21.44	16.8364
CH1_12_T1	Chap I	f23_1104, 6d	Triticum	5.32	3.06	2.6	1.74	poor	1	-26.2418	59.84163	6.344258	1.847903	37.78079	20.27377
CH1_12_T2	Chap I	f23_1104, 6d	Triticum	4.95	3.84	2.59	1.29	borderline	1	-24.4598	54.89822	8.35274	3.58203	17.88034	18.41006
CH1_12_T3	Chap I	f23_1104, 6d	Triticum		2.4	2.28	2.24	borderline	1	-21.8142	61.28331	15.94873	9.750072	7.332992	15.65576
CH1_13_H1	Chap I	f23_1104, 133	Hulled Hordeum	4.81	2.08	1.56	2.31	borderline	1	-23.993	56.68856	5.425088	2.818022	23.46917	17.92304
CH1_13_H2	Chap I	f23_1104, 133	Naked Hordeum	5.58	2.86	2.23	1.95	borderline	1	-23.6732	69.83005	6.104649	1.761111	46.25967	17.58959
CH1_13_H3	Chap I	f23_1104, 133	Hulled Hordeum	5.99	2.94	2.25	2.04	poor	1	-23.8521	65.51467	5.711007	2.030369	37.64527	17.77609
CH1_13_H5	Chap I	f23_1104, 133	Hulled Hordeum	4.6	2.47	1.85	1.86	poor	1	-22.63	63.97	4.73	3.67	17.43	16.50347
CH1_13_HH4	Chap I	f23_1104, 133	Hulled Hordeum	6.05	2.56	1.81	2.36	borderline	1	-24.43	61.954	4.73	2	30.49	18.379
CH1_13_HN1	Chap I	f23_1104, 133	Naked Hordeum	5.75	2.49	1.94	2.31	borderline	1	-22.5668	64.68075	14.15972	2.221841	33.96323	16.43776
CH1_13_HN2	Chap I	f23_1104, 133	Naked Hordeum	5.13	2.59	2.08	1.98	poor	1	-24.1659	64.35407	6.360366	2.426203	30.94537	18.1034
CH1_14_HN1	Chap I	f 31k_1134, #43	Naked Hordeum	5.76	2.88	2.31	2	poor	1	-24.6288	61.29391	6.373147	2.426324	29.47239	18.58653
CH1_14_HN2	Chap I	f 31k_1134, #43	Naked Hordeum	5.66	2.83	2.5	2	good	1	-23.6771	59.78078	8.002643	2.870146	24.2999	17.5937
CH1_14_HN4	Chap I	f 31k_1134, #43	Naked Hordeum	5.14	3.42	2.21	1.5	borderline	1	-22.9429	53.22636	9.473955	2.280816	27.22596	16.82904

Supplementary Table 3. Continued (Page 2 of 11)

CH1_14_T1	Chap I	f 31k_1134, #43	Triticum	4.9	3.19	2.44	1.54	good	1	-23.6397	60.68957	4.988024	3.959754	17.88103	17.5547
CH1_15_H1	Chap I	f12_L115, 3a	Hulled Hordeum	4.7	2.84	2.49	1.65	poor	1	-24.4	66.1	6.191478	2.2	34.6	18.34768
CH1_15_H2	Chap I	f12_L115, 3a	Hulled Hordeum	5.19	3.43	2.67	1.51	poor	1	-23.9	67.3	5.752057	2.3	33.4	17.82604
CH1_15_HN1	Chap I	f12_L115, 3a	Naked Hordeum	4.42	2.02	1.59	2.19	borderline	1	-23.2191	64.97427	3.657331	3.325701	19.54	17.11654
CH1_15_HN2	Chap I	f12_L115, 3a	Naked Hordeum	5.1	2.77	2.69	1.84	poor	1	-24.7	65.8	7.861075	2.6	29.7	18.66092
CH1_15_HN3	Chap I	f12_L115, 3a	Naked Hordeum		2.61	1.94		good	1	-24.7	61.5	7.291043	3.4	21	18.66092
CH1_15_T1	Chap I	f12_L115, 3a	Triticum	4.61	3.43	2.89	1.34	poor	1	-25.5821	67.68373	6.469913	2.087303	37.83081	19.58311
CH1_15_T2	Chap I	f12_L115, 3a	Triticum	5.5	2.73	2.16	2.01	poor	1	-24.2864	62.03298	6.72506	2.096155	34.52599	18.22912
CH1_2_H1	Chap I	F18_bag 47, sq, c4	Naked Hordeum	5.17	3.22	2.95	1.61	good	1	-24.99	21.14	5.79	1.8	11.51	18.96391
CH1_2_H2	Chap I	F18_bag 47, sq, c4	Naked Hordeum	6.01	3.3	2.6	1.82	good	1	-24.84	62.545	7.41	3.3	18.74	18.80717
CH1_2_H3	Chap I	F18_bag 47, sq, c4	Naked Hordeum		2.23	1.75		good	1	-25.85	57.343	7.25	3.6	15.74	19.86347
CH1_2_H4	Chap I	F18_bag 47, sq, c4	Naked Hordeum	4.26	2.37	2.11	1.8	good	1	-22.85	53.887	6.71	4.2	12.89	16.73233
CH1_2_H5	Chap I	F18_bag 47, sq, c4	Naked Hordeum	5.6	2.99	2.37	1.87	good	1	-26.42	57.557	5.06	3.3	17.3	20.46057
CH1_2_H6	Chap I	F18_bag 47, sq, c4	Naked Hordeum	4.5	2.58	1.77	1.74	borderline	1	-25.19	56.002	5.62	4.3	13.1	19.17297
CH1_2_H7	Chap I	F18_bag 47, sq, c4	Naked Hordeum		1.98	1.7		good	1	-25.39	52.235	5.72	4.2	12.36	19.38211
CH1_3_H1	Chap I	F 31m_L 144, 1136	Naked Hordeum		2.65	1.86		good	1	-23.6862	57.08922	2.98132	4.507103	14.77758	17.60319
CH1_3_H2	Chap I	F 31m_L 144, 1136	Naked Hordeum	4.61	2.67	2.32	1.73	good	1	-22.5081	57.45075	7.713653	2.27778	29.42597	16.37668
CH1_3_H3	Chap I	F 31m_L 144, 1136	Naked Hordeum	4.78	2.71	2.1	1.76	poor	1	-24.8088	63.31808	5.302364	1.77868	41.5314	18.77455
CH1_3_H4	Chap I	F 31m_L 144, 1136	Naked Hordeum		2.56	1.57		borderline	1	-23.845	60.50708	4.266057	2.340403	30.16215	17.7687
CH1_3_H5	Chap I	F 31m_L 144, 1136	Naked Hordeum		3.18	2.32		borderline	1	-23.9512	60.81529	9.093706	2.57727	27.52958	17.87943
CH1_3_H6	Chap I	F 31m_L 144, 1136	Naked Hordeum		3.1	2.31		poor	1	-25.1196	62.80468	5.359847	3.266232	19.22848	19.09979
CH1_3_T1	Chap I	F 31m_L 144, 1136	Triticum	3.52	2.89	2.41	1.22	good	1	-24.9827	57.40871	3.822939	1.780609	37.61455	18.9563
CH1_4_H1	Chap I	f 33_# 35, 145, 114	Naked Hordeum	3.51	2.33	1.74	1.51	poor	1	-22.1908	67.32667	2.430076	3.392932	23.15041	16.04692
CH1_4_H3	Chap I	f 33_# 35, 145, 114	Naked Hordeum	5.59	3.1	2.79	1.8	good	1	-24.9105	53.84282	10.35079	2.34044	26.83967	18.88087
CH1_4_H4	Chap I	f 33_# 35, 145, 114	Naked Hordeum	4.53	2.8	2.52	1.62	good	1	-24.5045	63.18292	9.99338	4.354336	16.92873	18.45682
CH1_4_H5	Chap I	f 33_# 35, 145, 114	Naked Hordeum	4.42	2.52	1.87	1.75	borderline	1	-22.5221	59.55479	4.426707	4.870953	14.26427	16.39124
CH1_4_H6	Chap I	f 33_# 35, 145, 114	Naked Hordeum	5.89	3.59	2.73	1.64	poor	1	-25.8871	67.35911	9.600534	1.923862	40.84785	19.90234
CH1_4_H7	Chap I	f 33_# 35, 145, 114	Naked Hordeum		2.58	1.93		good	1	-24.73	56.248	10.03	5.862403	9.59	18.69226
CH1_4_T1	Chap I	f 33_# 35, 145, 114	Triticum	3.58	2.82	2.46	1.27	good	1	-24.0279	62.46744	4.949152	2.972327	24.51907	17.95939

Supplementary Table 3. Continued (Page 3 of 11)

CH1_4_T2	Chap I	f 33_# 35, 145, 114	Triticum	3.77	3.31	3.15	1.14	poor	1	-21.8838	63.88097	2.281239	4.905799	15.19178	15.728
CH1_4_T3	Chap I	f 33_# 35, 145, 114	Triticum	3.99	3.29	2.78	1.21	poor	1	-24.2612	66.60162	2.76521	2.776967	27.98085	18.20278
CH1_5_H1	Chap I	f31 o_1139, A7	Naked Hordeum	4.2	3.03	2.47	1.39	good	1	-24.1039	62.06261	7.752185	2.684742	26.96959	18.03871
CH1_5_H2	Chap I	f31 o_1139, A7	Naked Hordeum	4.91	3.54	2.67	1.39	good	1	-24.4558	61.05552	5.408834	2.309052	30.84878	18.40597
CH1_5_H5	Chap I	f31 o_1139, A7	Naked Hordeum	4.67	3.35	1.78	1.39	poor	1	-24.3707	63.19717	8.285857	3.17446	19.90801	18.31637
CH1_5_HN1	Chap I	f31 o_1139, A7	Naked Hordeum	5.96	3.38	2.66	1.76	poor	1	-22.2027	64.35632	7.804913	2.505416	29.96802	16.05921
CH1_5_HN2	Chap I	f31 o_1139, A7	Naked Hordeum	4.55	2.98	2.19	1.53	poor	1	-24.1251	61.89191	6.138913	1.437669	50.2252	18.06086
CH1_5_T1	Chap I	f31 o_1139, A7	Triticum	4.18	2.88	2.37	1.45	good	1	-24.9281	62.9679	3.601887	1.780486	41.25983	18.89924
CH1_5_T2	Chap I	f31 o_1139, A7	Triticum	3.92	3.11	2.53	1.26	good	1	-23.93	58.56039	5.302364	3.426897	19.93653	17.85728
CH1_5_T3	Chap I	f31 o_1139, A7	Triticum	4.65	3.68	3.14	1.26	good	1	-23.4051	58.6605	4.518542	2.222931	30.78694	17.31024
CH1_6_H1	Chap I	F14 Bag 20, L114, D3, 1077	Naked Hordeum	5.24	2.6	1.9	2.02	poor	1	-22.89	61.91	5.45	3.4	18.17	16.77396
CH1_6_H4	Chap I	F14 Bag 20, L114, D3, 1077	Naked Hordeum		2.5	2.1		poor	1	-21.72	60.717	4.08	3.6	16.72	15.55792
CH1_6_H5	Chap I	F14 Bag 20, L114, D3, 1077	Naked Hordeum	5.68	3.33	2.57	1.71	poor	1	-24.94	64.77227	6.28	2.88	22.5	18.91166
CH1_6_H6	Chap I	F14 Bag 20, L114, D3, 1077	Naked Hordeum	4.95	2.53	2.04	1.96	poor	1	-24.77	63.2091	6.1	2.77	22.83	18.73404
CH1_6_HH1	Chap I	F14 Bag 20, L114, D3, 1077	Hulled Hordeum	6.12	3.81	2.69	1.61	borderline	1	-24.71	57.634	4.27	3.263	17.67	18.67137
CH1_6_HH2	Chap I	F14 Bag 20, L114, D3, 1077	Hulled Hordeum	5.94	2.87	2.03	2.07	poor	1	-24.09	65.772	5.59	3.014	21.82	18.0242
CH1_6_HH3	Chap I	F14 Bag 20, L114, D3, 1077	Hulled Hordeum	6.17	2.55	1.82	2.42	poor	1	-22.8	56.378	6.12	2.74	20.58	16.68031
CH1_6_HH4	Chap I	F14 Bag 20, L114, D3, 1077	Hulled Hordeum		2.73	2.16		poor	1	-22.94	54.923	11.6	4.1	13.32	16.82599
CH1_6_HH5	Chap I	F14 Bag 20, L114, D3, 1077	Hulled Hordeum	5.05	2.48	2.07	2.04	poor	1	-25.23	57.689	5.49	4	14.46	19.21479
CH1_6_HH6	Chap I	F14 Bag 20, L114, D3, 1077	Hulled Hordeum	5.41	2.02	1.53	2.68	borderline	1	-24.29	62.496	7.43	2.5	25.41	18.23288
CH1_6_HH7	Chap I	F14 Bag 20, L114, D3, 1077	Hulled Hordeum	4.79	2.34	1.76	2.05	borderline	1	-24.17	57.68	5.38	2.6	22.6	18.10766
CH1_6_T1	Chap I	F14 Bag 20, L114, D3, 1077	Triticum	4.12	2.88	2.45	1.43	borderline	1	-21.0546	56.30219	6.816162	5.652265	9.960997	14.86286
CH1_7_T1	Chap I	F12 1118	Triticum	3.61	3.24	1.97	1.11	borderline	1	-23.74	60.5109	4.68	3.16	19.14	17.65923
CH1_8_HN1	Chap I	NA	Naked Hordeum	4.82	3.03	2.79	1.59	borderline	1	-23.5003	57.83261	8.479591	6.542632	10.31257	17.40942
CH1_8_HN2	Chap I	layer 4_20	Naked Hordeum	5.14	3.06	2.63	1.68	good	1	-22.211	63.4614	8.111118	3.688757	20.07134	16.0679

Supplementary Table 3. Continued (Page 4 of 11)

CH1_8_HN3	Chap I	layer 4_20	Naked Hordeum	4.96	2.5	2.08	1.98	good	1	-24.5347	64.72259	4.870364	1.863769	40.5145	18.48831
CH1_8_HN4	Chap I	layer 4_20	Naked Hordeum	5.85	3.31	2.4	1.77	poor	1	-22.7647	62.81314	5.74121	2.441666	30.01311	16.64359
CH1_8_HN5	Chap I	layer 4_20	Naked Hordeum	5.33	3.17	2.54	1.68	borderline	1	-21.8582	62.5898	7.356049	3.030999	24.09154	15.70142
CH1_8_HN6	Chap I	layer 4_20	Naked Hordeum	5.51	2.45	1.86	2.25	poor	1	-21.8662	64.50845	13.31807	2.537082	29.66395	15.70972
CH1_8_HN7	Chap I	layer 4_20	Naked Hordeum	4.64	2.67	2.58	1.74	good	1	-23.8601	55.80695	6.739914	2.925816	22.25298	17.78443
CH1_8_HN8	Chap I	layer 4_20	Naked Hordeum	5.03	2.53	2.32	1.99	poor	1	-23.2964	71.19038	4.578404	2.494217	33.29921	17.19703
CH1_8_T1	Chap I	layer 4_20	Triticum	4.05	2.92	2.46	1.39	borderline	1	-22.7987	56.99808	3.025983	4.799289	13.85575	16.67894
CH1_8_T2	Chap I	layer 4_20	Triticum	4.15	3.36	3.03	1.24	good	1	-20.1282	57.24031	5.161317	2.858448	23.36245	13.90813
CH1_8_T3	Chap I	layer 4_20	Triticum	3.17	2.61	2.1	1.21	good	1	-24.2627	58.63774	10.08641	3.215358	21.27623	18.20436
CH1_9_HH1	Chap I	f18 a2, bag 5	Hulled Hordeum	5.95	2.81	2.68	2.12	borderline	1	-24.13	66.24	8.55	3.69	17.94	18.06593
CH1_9_HH2	Chap I	f18 a2, bag 5	Hulled Hordeum	6.5	3.51	2.66	1.85	poor	1	-25.29	55.75	4.25	2.4	23.22	19.27753
CH2_11_H1	Chap II	3.3_A8	Naked Hordeum	3.63	2.54	1.83	1.43	poor	1	-22.7286	61.89164	4.051628	2.276764	31.71472	16.60605
CH2_11_H10avg	Chap II	3.3_A8	Naked Hordeum	5.36	3.79	2.62	1.41	poor	1	-22.94	59.87951	8.321862	2.321299	30.37573	16.82601
CH2_11_H2	Chap II	3.3_A8	Naked Hordeum	5.57	4	2.77	1.39	poor	1	-24.347	66.95192	5.694669	1.953834	39.9781	18.29242
CH2_11_H3	Chap II	3.3_A8	Naked Hordeum	3.22	2.29	1.63	1.41	borderline	1	-23.3424	58.66814	6.152196	3.507402	19.51477	17.24495
CH2_11_H4	Chap II	3.3_A8	Naked Hordeum	5.93	2.94	2.5	2.02	good	1	-23.2947	55.21158	9.200472	3.448289	18.67985	17.19525
CH2_11_H5avg	Chap II	3.3_A8	Naked Hordeum	4.22	2.92	2.3	1.45	good	1	-23.2396	49.39694	4.952238	2.510525	27.37226	17.13786
CH2_11_H6	Chap II	3.3_A8	Naked Hordeum	4.67	3.07	2.58	1.52	poor	1	-23.4262	60.35793	4.473352	2.515301	27.99568	17.33223
CH2_11_H7	Chap II	3.3_A8	Naked Hordeum	4.54	2.9	2.1	1.57	borderline	1	-21.8937	62.61762	4.396858	2.268108	32.20917	15.73831
CH2_11_H8	Chap II	3.3_A8	Naked Hordeum	4.46	2.97	2.17	1.5	poor	1	-22.6408	59.34979	5.951902	1.942964	35.63701	16.51469
CH2_11_H9	Chap II	3.3_A8	Naked Hordeum	4.31	3.42	2.32	1.26	poor	1	-23.1336	63.00682	6.320274	2.158365	34.05725	17.02755
CH2_11_T1	Chap II	3.3_A8	Triticum	4.72	3.85	2.59	1.23	poor	1	-21.8767	39.63472	4.302423	1.935417	23.89175	15.7206
CH2_11_T2	Chap II	3.3_A8	Triticum	3.89	2.38	1.67	1.63	poor	1	-24.0381	45.22759	4.612706	1.403162	37.60472	17.97009
CH2_11_T3	Chap II	3.3_A8	Triticum	5.17	3.77	2.42	1.37	poor	1	-24.5013	58.61824	3.708357	1.586131	43.11621	18.45348
CH2_11_T4	Chap II	3.3_A8	Triticum	5.05	3.56	3.23	1.42	good	1	-25.5463	57.53738	6.123828	2.563352	26.18717	19.54559
CH2_11_T6	Chap II	3.3_A8	Triticum		3.05	1.93		good	1	-22.1765	63.94397	8.023812	3.021914	24.68677	16.03203
CH2_11_T7	Chap II	3.3_A8	Triticum	5.24	3.88	2.36	1.35	poor	1	-22.7589	50.91403	5.770225	2.836409	20.94186	16.63754
CH2_11_T8	Chap II	3.3_A8	Triticum	4.87	4.04	3	1.21	poor	1	-24.4524	63.1315	4.256081	2.939392	25.05736	18.40237
CH2_11_T9	Chap II	3.3_A8	Triticum	3.61	2.51	2.02	1.44	poor	1	-23.4121	60.93577	3.901422	3.950677	15.42413	17.31758

Supplementary Table 3. Continued (Page 5 of 11)

CH2_12_H1	Chap II	3.4 bag 1	Naked Hordeum	3.89	3.21	2.14	1.21	poor	1	-22.58	68.351	6.43	2.594	26.35	16.45147
CH2_12_H2	Chap II	3.4 bag 1	Naked Hordeum	4.12	2.63	2.29	1.57	good	1	-22.86	54.702	3.33	2.369	23.09	16.74274
CH2_13_H1	Chap II	3.4 bag 2	Naked Hordeum	4.59	3.34	2.83	1.37	good	1	-22.15	65.72	4.74	3.8	17.46	16.0045
CH2_13_H2	Chap II	3.4 bag 2	Naked Hordeum	4.14	2.86	2.33	1.45	poor	1	-24.04	62.873	3.95	2.3	27.08	17.97205
CH2_13_H3	Chap II	3.4 bag 2	Naked Hordeum	4.44	3.24	2.29	1.37	borderline	1	-22.49	54.40453	8.19	3.56	15.3	16.35789
CH2_13_HH1	Chap II	3.4 bag 2	Hulled Hordeum	4.4	3.38	2.4	1.3	borderline	1	-25.21	61.37078	4.19	2.74	22.4	19.19388
CH2_14_H1	Chap II	3.4 bag 3	Naked Hordeum	5.07	3.72	2.85	1.36	good	1	-23.44	56.585	4.31	2.718965	20.81	17.3466
CH2_14_H2	Chap II	3.4 bag 3	Naked Hordeum	4.22	3.1	2.6	1.36	borderline	1	-23.7	54.626	4.08	2.662	20.52	17.61754
CH2_14_T1	Chap II	3.4 bag 3	Triticum	4.73	3.1	2.43	1.53	good	1	-23.08	56.956	7.33	3.2	17.77	16.97171
CH2_14_T2	Chap II	3.4 bag 3	Triticum	3.83	2.96	2.34	1.29	borderline	1	-23.88	55.112	6.53	5.2	10.57	17.80519
CH2_14_T3	Chap II	3.4 bag 3	Triticum	4.19	2.52	1.91	1.66	good	1	-23.46	56.956	5.87	3	19.21	17.36744
CH2_14_T4	Chap II	3.4 bag 3	Triticum	3.32	2.13	1.96	1.56	good	1	-23.21	57.009	4.25	3.4	16.61	17.10705
CH2_14_T5	Chap II	3.4 bag 3	Triticum	4.06	3.08	2.78	1.32	good	1	-22.18	53.216	3.87	4	13.38	16.03567
Ch2_16_T1	Chap II	3.6F	Triticum	4.24	3.23	2.27	1.31	good	1	-21.21	55.781	7.5	6.8	8.24	15.02876
Ch2_16_T2	Chap II	3.6F	Triticum	4.02	2.95	2.55	1.36	borderline	1	-24.91	59.86	3.83	3.75	15.96	18.88031
Ch2_16_T3	Chap II	3.6F	Triticum	3.75	2.69	2.21	1.39	good	1	-23.87	58.748	5.87	3.5	16.92	17.79476
Ch2_16_T4	Chap II	3.6F	Triticum	4.29	3.07	2.55	1.4	poor	1	-23.53	53.794	2.91	4.1	13.23	17.44037
Ch2_16_T5	Chap II	3.6F	Triticum		3.35	2.38		poor	1	-24.82	58.783	4.79	4	14.53	18.78628
CH2_18_H1avg	Chap II	3.7_Flot f	Naked Hordeum	4.53	3.63	3.08	1.25	poor	1	-23.137	58.34491	4.381432	2.810088	24.93108	17.03105
CH2_18_H2avg	Chap II	3.7_Flot f	Naked Hordeum	3.76	3.07	2.48	1.22	borderline	1	-24.6402	60.10925	3.521469	2.29955	30.63069	18.59842
CH2_18_H3	Chap II	3.7_Flot f	Naked Hordeum	3.97	3.08	2.47	1.29	poor	1	-24.251	63.98936	2.281193	1.765651	42.28143	18.19217
CH2_18_H4	Chap II	3.7_Flot f	Naked Hordeum	3.98	3.05	2.53	1.3	poor	1	-25.0879	59.63131	5.736511	2.550595	27.27594	19.06622
CH2_18_H5	Chap II	3.7_Flot f	Naked Hordeum	4.44	3.4	3.02	1.31	poor	1	-25.3534	63.73848	4.676665	1.869224	39.78206	19.34383
CH2_18_H6avg	Chap II	3.7_Flot f	Naked Hordeum	4.89	3.63	2.8	1.35	good	1	-23.6698	60.42372	4.730264	2.482552	28.66536	17.58611
CH2_18_H7	Chap II	3.7_Flot f	Naked Hordeum	4.83	3.42	2.54	1.41	poor	1	-23.832	65.38637	4.748127	1.610886	47.35537	17.75518
CH2_18_T1	Chap II	3.7_Flot f	Triticum	3.81	2.59	2.07	1.47	good	1	-22.5096	69.51795	4.198577	2.915051	27.8226	16.37822
CH2_18_T2	Chap II	3.7_Flot f	Triticum	5.52	4.16	2.89	1.33	poor	1	-24.737	67.20915	4.028406	1.632555	48.02942	18.69957
CH2_18_T3	Chap II	3.7_Flot f	Triticum	4.11	3.15	2.29	1.3	poor	1	-23.552	66.31187	4.260111	2.80474	27.58325	17.46325
CH2_18_T4	Chap II	3.7_Flot f	Triticum	4.72	2.93	2.53	1.61	good	1	-22.0772	59.90381	5.24637	3.910029	17.87398	15.9289

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CH2_18_T7avg	Chap II	3.7_Flot f	Triticum	4.64	3.53	2.46	1.31	poor	1	-22.6197	61.67822	7.536776	2.762367	26.62149	16.49281
CH2_19_H1	Chap II	3.8_f1	Naked Hordeum	4.13	2.83	2.17	1.46	poor	1	-24.4163	65.54478	3.434299	3.061754	21.41	18.36473
CH2_19_H2	Chap II	3.8_f1	Naked Hordeum	5.09	3.79	3.07	1.34	poor	1	-24.5096	65.65131	3.911349	1.425967	53.71315	18.4621
CH2_19_H3	Chap II	3.8_f1	Naked Hordeum	4.3	4.26	2.54	1.01	poor	1	-24.7489	63.873	4.758804	2.393193	31.13768	18.71205
CH2_19_H4	Chap II	3.8_f1	Naked Hordeum	4.28	3.27	2.57	1.31	poor	1	-24.0814	59.65935	6.242102	2.362157	29.46569	18.01522
CH2_19_T2	Chap II	3.8_f1	Triticum	4.24	3.5	2.33	1.21	poor	1	-21.6192	64.14428	4.500994	4.260351	15.0561	15.45329
CH2_2_H1	Chap II	F2.2 1114	Naked Hordeum	4.75	3.38	2.62	1.41	poor	1	-22.23	53.19	5.78	2.39	22.21	16.08763
CH2_2_H2	Chap II	F2.2 1114	Naked Hordeum	6.41	3.75	2.52	1.71	poor	1	-23.49	62.97	6.06	2.92	21.56	17.3987
CH2_2_H3	Chap II	F2.2 1114	Naked Hordeum	4.94	4.09	2.72	1.21	poor	1	-23.41	63.76	7.48	3.1	20.57	17.31535
CH2_2_H4	Chap II	F2.2 1114	Naked Hordeum	3.65	2	0.91	1.83	borderline	1	-21.97	56.081	7.62	4.2	13.22	15.81751
CH2_2_H5	Chap II	F2.2 1114	Naked Hordeum	3.59	2.35	1.73	1.53	borderline	1	-23.41	60.987	6.55	3.298	18.49	17.31535
CH2_2_T1	Chap II	F2.2 1114	Triticum	4.26	3.4	2.57	1.25	good	1	-23.02	61.855	4.93	3.4	17.96	16.90925
CH2_2_T2	Chap II	F2.2 1114	Triticum	3.3	2.96	2.23	1.11	good	1	-22.33	55.242	4.57	4.6	12.14	16.19156
CH2_2_T3	Chap II	F2.2 1114	Triticum	4.51	3.07	2.28	1.47	borderline	1	-22.86	59.97	3.6	3.4	17.75	16.74274
CH2_2_T4	Chap II	F2.2 1114	Triticum	3.74	2.97	2.49	1.26	poor	1	-23.8	56.04	4.78	3	18.37	17.72178
CH2_20_H1	Chap II	3.8_f2	Naked Hordeum	4.18	4.08	2.88	1.02	poor	1	-23.8834	65.65022	5.610308	2.724497	28.11231	17.80878
CH2_20_H2	Chap II	3.8_f2	Naked Hordeum	4.47	3.98	2.58	1.12	poor	1	-23.2906	65.56196	4.763866	1.592992	48.0159	17.19102
CH2_21_H1	Chap II	L4.5 D6 F1	Naked Hordeum	3.75	2.82	2.63	1.33	borderline	1	-22.76	57.23	10.78	3.914	14.62	16.6387
CH2_21_T1	Chap II	L4.5 D6 F1	Triticum	4.3	2.8	2.33	1.54	poor	1	-22.31	64.485	5.78	3.5	18.37	16.17077
CH2_21_T2	Chap II	L4.5 D6 F1	Triticum	4.24	3.12	2.33	1.36	poor	1	-22.32	62.4	5.78	4.12	15.14	16.18116
CH2_21_T3	Chap II	L4.5 D6 F1	Triticum	3.82	2.95	2.38	1.29	poor	1	-21.26	65.324	7.68	4.2	15.52	15.08061
CH2_21_T4	Chap II	L4.5 D6 F1	Triticum	3.94	3.69	2.41	1.07	poor	1	-25.0137	49.84488	6.120124	3.476908	14.33598	18.98481
CH2_21_T5	Chap II	L4.5 D6 F1	Triticum	4.53	3.18	2.3	1.42	poor	1	-23.6191	53.98296	6.372376	2.790551	19.34491	17.53416
CH2_22_H10	Chap II	4.7_	Naked Hordeum	4.96	3.05	2.64	1.63	borderline	1	-23.9481	64.38251	4.599843	2.825699	26.58207	17.87618
CH2_22_H1avg	Chap II	4.7_	Naked Hordeum	4.65	3.58	2.65	1.3	borderline	1	-24.4682	59.26559	3.657758	1.999735	35.35555	18.41886
CH2_22_H2	Chap II	4.7_	Naked Hordeum	4	2.99	2.21	1.34	borderline	1	-23.7991	61.11744	3.998183	3.279248	21.74391	17.72083
CH2_22_H3	Chap II	4.7_	Naked Hordeum	5.62	3.55	2.84	1.58	good	1	-24.3349	57.20559	5.638254	2.577972	25.88851	18.27973
CH2_22_H4	Chap II	4.7_	Naked Hordeum	4.93	2.9	2.82	1.7	poor	1	-24.2369	54.93741	7.05704	4.243105	15.10536	18.17742
CH2_22_H5	Chap II	4.7_	Naked Hordeum	4.67	3.58	2.28	1.3	borderline	1	-23.8062	59.00088	4.270185	3.792213	18.1515	17.72822

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CH2_22_H6	Chap II	4.7_	Naked Hordeum	4.3	2.64	2.17	1.63	good	1	-23.2197	56.93928	9.250843	8.486733	7.827412	17.11719
CH2_22_H7avg	Chap II	4.7_	Naked Hordeum	3.43	3.21	2.6	1.07	good	1	-23.7362	60.95409	3.331144	2.588834	27.524	17.65532
CH2_22_H8	Chap II	4.7_	Naked Hordeum	3.86	2.54	2.3	1.52	good	1	-23.4132	57.17485	6.514705	4.639082	14.3787	17.31868
CH2_22_H9	Chap II	4.7_	Naked Hordeum	4.48	2.22	2.13	2.02	poor	1	-23.5988	58.672	5.3168	4.555307	15.02657	17.5121
CH2_22_T1	Chap II	4.7_	Triticum	3.97	2.95	2.28	1.35	borderline	1	-24.5405	60.10341	4.717477	3.824483	18.33467	18.49437
CH2_22_T2	Chap II	4.7_	Triticum	4.17	3.25	2.48	1.28	good	1	-23.3028	59.78436	5.366252	3.045887	22.89922	17.20369
CH2_22_T3	Chap II	4.7_	Triticum	3.51	2.32	2.15	1.51	good	1	-23.1853	60.803	7.566446	3.567873	19.88211	17.08134
CH2_22_T4	Chap II	4.7_	Triticum	3.1	2.48	1.86	1.25	good	1	-23.83	67.4	3.7	3.28	20.55	17.75306
CH2_22_T5	Chap II	4.7_	Triticum	4.09	3.85	2.96	1.06	good	1	-23.32	61.92	5.26	4.54	13.64	17.22161
CH2_22_T6	Chap II	4.7_	Triticum	4.29	2.34	2.09	1.83	good	1	-23.3442	58.982	5.685233	2.729572	25.20994	17.24676
CH2_22_T7	Chap II	4.7_	Triticum	4.31	2.72	1.99	1.58	borderline	1	-23.3543	65.38706	3.86275	2.639407	28.90229	17.25728
CH2_22_T9avg	Chap II	4.7_	Triticum	3.39	2.89	2.28	1.17	good	1	-23.0415	59.9238	3.936696	2.677917	30.94737	16.93161
CH2_4_H1	Chap II	2.41 SE	Naked Hordeum	4.34	3.21	2.19	1.35	borderline	1	-23.09	59.982	6.85	4.2	14.28	16.98212
CH2_4_T1	Chap II	2.41 SE	Triticum	3.45	2.61	2.12	1.32	borderline	1	-23.83	38.358	2.81	2.2	17.44	17.75306
CH2_4_T2	Chap II	2.41 SE	Triticum	4.27	3.47	2.57	1.23	poor	1	-23.67	62.631	7.82	2.9	21.46	17.58627
CH2_4_T3	Chap II	2.41 SE	Triticum	4.07	3.24	2.49	1.26	poor	1	-23.55	61.01	5.47	3.9	15.5	17.46121
CH2_4_T4	Chap II	2.41 SE	Triticum	4.53	3.55	2.71	1.28	poor	1	-23.12	61.657	3.92	3.3	18.53	17.01335
CH2_4_T5	Chap II	2.41 SE	Triticum	3.35	2.7	2.07	1.24	borderline	1	-21.03	54.99	8.83	4.47	12.31	14.84213
CH2_5_HH1	Chap II	2.6_	Hulled Hordeum	5.79	3.14	2.58	1.84	good	1	-23.4152	57.93149	5.60098	5.615728	12.03526	17.32079
CH2_5_HH2	Chap II	2.6_	Hulled Hordeum	4.53	2.55	1.78	1.78	borderline	1	-23.9004	57.98067	4.086836	2.177077	31.07108	17.82644
CH2_5_HN1	Chap II	2.6_	Naked Hordeum	4.83	2.78	1.75	1.74	poor	1	-24.5091	54.50729	5.881041	3.231042	19.68153	18.46158
CH2_5_HN2	Chap II	2.6_	Naked Hordeum	5.37	3.11	2.27	1.73	poor	1	-24.9991	52.99654	5.537224	2.036344	30.3629	18.97337
CH2_5_HN4	Chap II	2.6_	Naked Hordeum	5.85	3.02	2.68	1.94	poor	1	-23.2734	58.89433	9.034248	3.478716	19.75156	17.1731
CH2_5_HN5	Chap II	2.6_	Naked Hordeum	5.14	3.12	2.46	1.65	borderline	1	-22.7265	60.64942	8.530541	3.02027	23.42759	16.60382
CH2_5_HN6	Chap II	2.6_	Naked Hordeum	4.69	2.65	2.28	1.77	poor	1	-24.3065	67.80675	4.080817	1.9596	40.36941	18.25011
CH2_5_HN7	Chap II	2.6_	Naked Hordeum	5.45	2.35	2.15	2.32	poor	1	-22.8683	62.42769	7.404252	1.983616	36.71694	16.75135
CH2_6_HN1avg	Chap II	3.1_A	Naked Hordeum	4.45	3.63	2.87	1.23	poor	1	-23.7257	63.94777	6.887741	2.367034	33.12073	17.6443
CH2_6_HN2	Chap II	3.1_A	Naked Hordeum		2.58	2.13		poor	1	-25.131	57.48494	5.852833	2.388735	28.07585	19.11129
CH2_6_HN3	Chap II	3.1_A	Naked Hordeum	4.18	3.2	2.46	1.31	poor	1	-23.407	60.28128	3.934874	2.198574	31.98808	17.31225

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CH2_6_HN4	Chap II	3.1_A	Naked Hordeum		3.45	2.6		poor	1	-24.5751	60.9624	5.515081	2.00585	35.4577	18.53044
CH2_6_T1avg	Chap II	3.1_A	Triticum					good	1	-23.3	64	8.983699	2.3	32.8	17.20078
CH2_7_H1	Chap II	3.1_C	Naked Hordeum	5.35	3.11	2.27	1.72	poor	1	-23.6947	47.67374	5.324852	1.79897	30.91733	17.61205
CH2_7_T1	Chap II	3.1_C	Triticum	3.49	3.4	2.39	1.03	poor	1	-22.3588	63.96747	5.335022	3.486291	21.40633	16.2215
CH2_7_T3	Chap II	3.1_C	Triticum	3.45	2.26	1.99	1.53	poor	1	-22.0215	56.13771	4.593565	2.554347	25.64021	15.87103
CH2_8_T1	Chap II	2.7/3.8_	Triticum	5.24	3.77	2.88	1.39	poor	1	-22.5918	67.87311	5.145575	2.945995	26.87896	16.46371
CH2_8_T2	Chap II	2.7/3.8_	Triticum	4.72	3.35	2.89	1.41	borderline	1	-21.7707	62.12292	4.038923	2.868149	25.26952	15.61055
CH2_8_T3	Chap II	2.7/3.8_	Triticum	5.14	2.8	2.14	1.84	poor	1	-21.4526	63.81696	7.317367	3.149227	23.64172	15.28038
CH2_8_T4	Chap II	2.7/3.8_	Triticum	4.01	2.52	2.31	1.59	borderline	1	-24.754	66.55221	4.302171	2.509541	30.93962	18.71733
CH2_8_T5	Chap II	2.7/3.8_	Triticum		2.43	1.69		good	1	-22.715	60.54511	5.1881	2.625504	26.90378	16.59186
CH2_9_H1	Chap II	2.7 F	Naked Hordeum	4.67	3.31	2.47	1.41	poor	1	-22.74	65.633	5.4	2.71	24.22	16.61789
CH2_9_H3	Chap II	2.7 F	Naked Hordeum	3.49	2.79	2.08	1.25	poor	1	-23.32	60.402	5.83	4.1	14.77	17.22161
CH2_9_H5	Chap II	2.7 F	Naked Hordeum	4.29	3.18	2.39	1.35	poor	1	-23.75	63.83	3.56	2.52	25.37	17.66965
CH2_9_T1	Chap II	2.7 F	Triticum	4.48	3.39	2.36	1.32	borderline	1	-23.82	52.443	6.33	3.234	16.22	17.74263
CH2_9_T2	Chap II	2.7 F	Triticum	3.78	2.71	1.53	1.39	poor	1	-23.61	61.159	6.49	3.9	15.54	17.52374
CH2_9_T3	Chap II	2.7 F	Triticum	3.35	2.65	2.44	1.26	poor	1	-23.24	60.68	5.57	3.96	15.33	17.13829
CH2_9_T5	Chap II	2.7 F	Triticum	3.95	2.82	2.15	1.4	borderline	1	-24.05	52.67	4.84	3.19	16.49	17.98248
Ch1_1.C1	Chap I	F18_bag 47, sq, c4	Cyperaceae carex						12	-24.69	57.22	4.54	4.1	14.33927	18.65048
Ch1_1.G1	Chap I	F18_bag 47, sq, c4	Galium						10	-25.05	59.605	7.37	7.7	7.071085	19.02662
Ch1_1.G2	Chap I	F18_bag 47, sq, c4	Galium						10	-25.52	62.205	8.14	4.4	13.14004	19.5181
Ch1_1.M1	Chap I	F18_bag 47, sq, c4	Wild Fabaceae (medicago)						18	-21.84	59.8	2.64	3.7	15.57582	15.68251
Ch1_1.P1	Chap I	F18_bag 47, sq, c4	Wild Poaceae (poaceae)						6	-21.41	61	6.23	8.1	7.25635	15.23621
CH1_10.C1	Chap I	f18_49, square 5	Cyperaceae carex						9	-25.7	60.85	5.25	1.3	15.83682	19.70646
CH1_10.G1	Chap I	f18_49, square 5	Galium						9	-25.19	64.61	7.04	3.4	17.27955	19.17297
CH1_10.G2	Chap I	f18_49, square 5	Galium						9	-25.02	61.704	7.7	1.2	16.07852	18.99526
CH1_10.M1	Chap I	f18_49, square 5	Wild Fabaceae (medicago)						12	-22.81	55.928	1.64	3.1	18.31948	16.69072
CH1_11.G1	Chap I	F18_34	Galium						12	-24.66	64.26	7.81	2.9	20.3605	18.61915
CH1_11.M1	Chap I	F18_34	Wild Fabaceae (medicago)						12	-22.17	62.113	2.38	2.3	20.77662	16.02528
CH1_11.P1	Chap I	F18_34	Wild Poaceae (poaceae)						6	-23.6	62.255	6.46	4.1	14.05389	17.51331

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CH1_13_G1AVG	Chap I	f23_1104, 133	Galium							12	-24.54	63.89	6.75	4.22	15.14	18.49384
CH1_13_M1	Chap I	f23_1104, 133	Wild Fabaceae (medicago)							12	-22.12	64.7	1.49	7.73	8.37	15.97333
CH1_13_P1	Chap I	f23_1104, 133	Wild Poaceae (poa)							6	-22.87	66.13	5.14	5.29	12.51	16.75314
CH1_14_C1	Chap I	f 31k_1134, #43	Cyperaceae carex							4	-24.9619	61.42246	5.84044	5.238812	11.72	18.93453
CH1_14_G1AVG	Chap I	f 31k_1134, #43	Galium							9	-24.8808	60.25831	7.106703	4.768166	12.63771	18.84981
CH1_14_M1	Chap I	f 31k_1134, #43	Wild Fabaceae (medicago)							12	-23.066	60.35307	2.235749	7.77383	7.76	16.95708
CH1_15_G1AVG	Chap I	f12_1115, 3a	Galium							12	-24.9559	62.82804	7.177933	4.28649	14.66	18.92831
CH1_15_M1	Chap I	f12_1115, 3a	Wild Fabaceae (medicago)							7	-23.64	66.06	0.58	7.53	8.78	17.555
CH1_15_P1AVG	Chap I	f12_1115, 3a	Wild Poaceae (poaceae bromus)							6	-23.2189	63.63973	6.962016	5.622657	11.34	17.11632
CH1_2.C1	Chap I	F27_L_140 bag 42	Cyperaceae carex							8	-24.49	58.614	6.5	3.5	15.51026	18.44164
CH1_2.CH1	Chap I	F27_L140 bag 42_L_140 bag 42	Chenopodium							18	-22.81	59.631	9.82	8.1	7.217827	16.69072
CH1_2.M1	Chap I	F27_L_140 bag 42	Wild Fabaceae (Medicago/trigonella)							15	-22.85	60.899	2.3	1.9	11.09385	16.73233
CH1_2.P1	Chap I	F27_L_140 bag 42	Wild Poaceae (poaceae)							8	-24.17	59.961	5.53	3.8	14.78539	18.10766
CH1_3_G1	Chap I	F 31m_L_144, 1136	Galium							16	-25.2021	62.06378	7.208776	4.669652	13.29	19.18566
CH1_3_M1	Chap I	F 31m_L_144, 1136	Wild Fabaceae (medicago)							20	-22.0629	63.20412	2.436679	8.310918	7.6	15.91403
CH1_4_C1AVG	Chap I	f 33_# 35, 145, 114	Cyperaceae carex							26	-25.4613	60.29738	4.355294	2.577918	23.44	19.45669
CH1_4_CH1	Chap I	f 33_# 35, 145, 114	Chenopodium							20	-30.1843	63.79128	6.858153	3.067909	20.79	24.42139
CH1_4_G1AVG	Chap I	f 33_# 35, 145, 114	Galium							12	-25.7447	62.75452	6.618041	4.614195	13.6	19.75324
CH1_4_M1	Chap I	f 33_# 35, 145, 114	Wild Fabaceae (medicago)							13	-22.32	64.8	2.14	8.35	7.76	16.18116
CH1_4_P1	Chap I	f 33_# 35, 145, 114	Wild Poaceae (poa)							8	-23.8858	63.8027	7.320292	7.777583	8.2	17.81122
CH1_5_CH1	Chap I	31 o_1139, A7	Chenopodium							26	-23.9969	61.85298	10.76223	4.454773	13.88	17.9271
CH1_5_G1AVG	Chap I	31 o_1139, A7	Galium							6	-24.9593	58.65236	10.35462	4.890463	11.99316	18.93183
CH1_5_M1AVG	Chap I	31 o_1139, A7	Wild Fabaceae (medicago)							20	-22.0426	61.63752	2.430367	8.09784	7.61	15.89287
CH1_6.C1	Chap I	F14_Bag 20, L114, D 3, 1077	Cyperaceae carex							19	-23.23	59.475	5.77	3.6	14.46816	17.12788
CH1_6.CH1	Chap I	F14_Bag 20, L114, D 3, 1077	Chenopodium							26	-25.88	61.292	10.59	5	10.86	19.89488
CH1_6.G1	Chap I	F14_Bag 20, L114, D 3, 1077	Galium							10	-25.26	60.559	8.52	5.8	16.26522	19.24616
CH1_6.G2	Chap I	F14_Bag 20, L114, D 3, 1077	Galium							10	-24.35	61.756	8.62	7.1	8.232596	18.2955

Supplementary Table 3. Continued (Page 10 of 11)

CH1_6M1	Chap I	F14_Bag 20, L114, D 3, 1077	Wild Fabaceae (medicago)							20	-21.79	62.024	2.28	4.5	12.95517	15.63059
CH1_6P1	Chap I	F14_Bag 20, L114, D 3, 1077	Wild Poaceae (poaceae)							8	-23.59	62.28	7.52	1.5	19.58861	17.50289
CH1_7C1	Chap I	F12_1118	Cyperaceae carex							19	-24.7	63.99712	6.17	2.7	20.65807	18.66092
CH1_7CH1	Chap I	F12_1118	Chenopodium							23	-18.95	64.46	9.31	8.5	6.443181	12.69048
CH1_7M1	Chap I	F12_1118	Wild Fabaceae (medicago/trigonella)							8	-22.26	59.74759	4.91	2.8	19.39899	16.1188
CH1_9C1	Chap I	f18_a2, bag 5	Cyperaceae carex							16	-25.34	58.001	4.8	3.8	14.7442	19.32982
CH1_9CH1	Chap I	f18_a2, bag 5	Chenopodium							36	-26.08	59.08	9.47	3.5	16.49781	20.10432
CH1_9G1	Chap I	f18_a2, bag 5	Galium							10	-26	64.142	6.4	3.2	16.70319	20.02053
CH1_9G2	Chap I	f18_a2, bag 5	Galium							10	-26.02	60.95	8.27	3.1	17.29832	20.04148
CH1_9M1	Chap I	f18_a2, bag 5	Wild Fabaceae (medicago)							12	-22.43	61.01	2.48	3.3	17.68517	16.29551
CH1_9P1	Chap I	f18_a2, bag 5	Wild Poaceae (poaceae)							7	-23.52	65.653	5.29	8	6.938875	17.42995
CH2_1C1	Chap II	F2.1_113	Cyperaceae carex							22	-24.41	66.2	9.02	49.8	0.40371	18.35812
CH2_1CH1	Chap II	F2.1_113	Chenopodium							28	-21.66	63.61	5.91	49.5	0.403832	15.49564
CH2_1G1	Chap II	F2.1_113	Galium							12	-25.4	62.47	6.17	48.8	0.40836	19.39257
CH2_11_G1	Chap II	3.3_A8	Galium							6	-25.99	63.03	4.72	3.26	19.31	20.01006
CH2_11_M1	Chap II	3.3_A8	Wild Fabaceae (medicago/trigonella)							8	-22.16	61.86	1.18	6.83	9.06	16.01489
CH2_123_M1	Chap II	F2.1, F2.2 & F2.3_111 3 & 1114	Wild Fabaceae (medicago/trifolium)							9	-23.33	62.101	6.06	2.3	17.97815	17.23202
CH2_16CH1	Chap II	F3.6F	Chenopodium							30	-25.91	65.535	8.16	10.1	6.404927	19.92629
CH2_19_8_G1	Chap II	3.8+2.7/2.8_F1	Galium							6	-27.1	61.8	3.97	3.56	17.37	21.17381
CH2_2C1	Chap II	F2.2_1114	Cyperaceae carex							12	-24.62	62.228	5.67	2.4	17.27748	18.57737
CH2_2C2	Chap II	F2.2_1114	Cyperaceae carex							12	-24.45	61.451	1.99	2.1	19.37178	18.39988
CH2_2CH1	Chap II	F2.2_1114	Chenopodium							28	-22.58	65.143	6.31	10.8	6.318587	16.45147
CH2_20.19_CH1	Chap II	3.8_F2,F1	Chenopodium							16	-24.03	63.79	10.41	4.02	15.87	17.96162
CH2_20_M1	Chap II	3.8_f2	Wild Fabaceae (medicago)							5	-22.96	64.41	0.81	9.59	6.71	16.8468
CH2_21C1	Chap II	L4.5_D6 F1	Cyperaceae carex							15	-25.6907	57.38671	6.648403	3.426295	16.74891	19.69599
CH2_21CH1	Chap II	L4.5_D6 F1	Chenopodium							30	-26.03	60.25	7.26	3.46	17.41	20.05195
CH2_22_C1	Chap II	4.7	Cyperaceae carex							16	-24.94	63.96	5.58	2.93	21.83	18.91166
CH2_22_CH1	Chap II	4.7	Chenopodium							28	-20.51	62.14	8.75	4	15.55	14.30336

Supplementary Table 3. Continued (Page 11 of 11)

Supplementary Table 4. Analysis of independent group contrasts, displayed in Supplementary Figure 3, of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of naked and hulled barley.

Mean Difference					
Outcome variable	Site Effect	M	95% CI		n
			LL	UL	
$\Delta^{13}\text{C}$	Naked Hordeum	17.6	17.4	17.8	114
	Hulled Hordeum	18.0	17.5	18.5	18
	Naked Hordeum – Hulled Hordeum	-0.4	-0.9	0.1	
$\delta^{15}\text{N}$	Naked Hordeum	6.2	5.8	6.6	114
	Hulled Hordeum	5.8	4.9	6.8	18
	Naked Hordeum – Hulled Hordeum	0.3	-0.7	1.4	
Note. Variances are assumed equal, so s_p was used to calculate each CI.					

Supplementary Table 5. Analysis of independent group contrasts, displayed in Supplementary Figure 4Supplementary Figure 3, of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of wheat and barley grains between Chap I and II

Mean Difference						
Taxa	Outcome variable	Site Effect	M	95% CI		n
				LL	UL	
Naked barley	$\Delta^{13}\text{C}$	Chap I	17.7	17.4	18.0	53
		Chap II	17.5	17.2	17.8	61
		Chap I – Chap II	0.2	-0.2	0.6	
	$\delta^{15}\text{N}$	Chap I	6.9	6.3	7.4	53
		Chap II	5.6	5.1	6.1	61
		Chap I – Chap II	1.3	0.5	2.0	
Hulled barley	$\Delta^{13}\text{C}$	Chap I	18.0	17.5	18.4	15
		Chap II	18.1	17.1	19.1	3
		Chap I – Chap II	-0.1	-1.2	1.0	
	$\delta^{15}\text{N}$	Chap I	6.1	5.1	7.1	15
		Chap II	4.6	2.4	6.8	3
		Chap I – Chap II	1.5	-1.0	3.9	
All Barley	$\Delta^{13}\text{C}$	Chap I	17.8	17.5	18.0	68
		Chap II	17.5	17.3	17.8	64
		Chap I – Chap II	0.3	-0.1	0.6	
	$\delta^{15}\text{N}$	Chap I	6.7	6.2	7.2	68
		Chap II	5.5	5.1	6.0	64
		Chap I – Chap II	1.1	0.5	1.8	
Wheat	$\Delta^{13}\text{C}$	Chap I	17.6	17.1	18.1	25
		Chap II	17.1	16.8	17.4	58
		Chap I – Chap II	0.5	-0.1	1.1	
	$\delta^{15}\text{N}$	Chap I	6.0	5.2	6.8	25
		Chap II	5.3	4.8	5.9	58
		Chap I – Chap II	0.6	-0.3	1.6	
Note. Variances are assumed equal, so s_p was used to calculate each CI.						

Supplementary Table 6. Analysis of independent group contrasts, displayed in Supplementary Figure 5, of $\delta^{15}\text{N}$ of all wheat and barley grains.

Outcome variable	Genus Effect	M	95% CI		n
			LL	UL	
$\delta^{15}\text{N}$	Triticum	5.5	5.1	6.0	83.0
	Hordeum	6.1	5.8	6.5	132.0
	Hordeum - Triticum	0.6	0.0	1.2	
Note. Variances are assumed equal, so s_p was used to calculate each CI.					

Supplementary Table 7. Percentages and counts of taxa, grouped by habitat type: Grassland, Ruderal, and Wetland, for Chap I and II.

	Chap II		Chap I	
	Percentage	N	Percentage	N
Grassland	19.81%	507	9.22%	2433
Amaranthaceae			0.06%	15
<i>Atriplex</i> sp.	3.01%	77		
<i>Bassia</i> cf. <i>scoparia</i> / <i>Atriplex</i> sp.	1.29%	33	0.13%	34
<i>Salsola kali</i>	1.88%	48	1.99%	524
<i>Bassia</i> cf. <i>scoparia</i>	0.23%	6		
Amaryllidaceae			0.30%	80
Asteraceae	0.12%	3		
<i>Artemisia campestris</i>	0.12%	3		
Fabaceae			0.35%	93
<i>Astragalus</i> / <i>Medicago</i> spp.	0.08%	2		
<i>Hippocrepis comosa</i>	0.04%	1		
Lamiaceae	0.43%	11		
cf. <i>Thymus</i> sp.	0.16%	4		
<i>Clinopodium</i> sp.	0.04%	1		1
<i>Lamiaceae</i>	0.08%	2	1.03%	273
<i>Origanum</i> cf. <i>vulgare</i>			0.01%	2
<i>Prunella</i> sp.	0.12%	3		
<i>Stachys</i> cf. <i>alpina</i>	0.04%	1		
Poaceae	2.23%	57	1.61%	426
<i>Agrostis</i> sp.	0.04%	1	0.11%	28
<i>Bromus</i> sp.	1.29%	33	1.56%	412
<i>Bromus</i> / <i>Elytrigia</i> / <i>Leymus</i> sp.	0.16%	4		
<i>Eragrostis</i> sp.	5.35%	137		
<i>Festuca</i> sp.			0.22%	59
<i>Hordeum vulgare</i> subsp. <i>spontaneum</i>			0.14%	38
<i>Milium</i> sp.			0.13%	34
<i>Panicoid</i> type (inflorescences) cf. <i>Eragrostis</i>	2.11%	54	0.07%	19
<i>Stipa</i> type	0.08%	2	1.16%	307
<i>Taeniatherum</i> sp.			0.03%	7
Rosaceae				
<i>Fragaria</i> sp.			0.02%	4
<i>Potentilla</i> sp.			0.14%	38
Ruderal	74.17%	1898	48.92%	12910
Amaranthaceae				
<i>Anthriscus</i> sp.	0.20%	5		
<i>Chenopodium hybridum</i>	0.04%	1		
<i>Chenopodium</i> spp.	66.82%	1710	24.70%	6519
Amaryllidaceae				
<i>Allium</i> sp.			0.16%	42

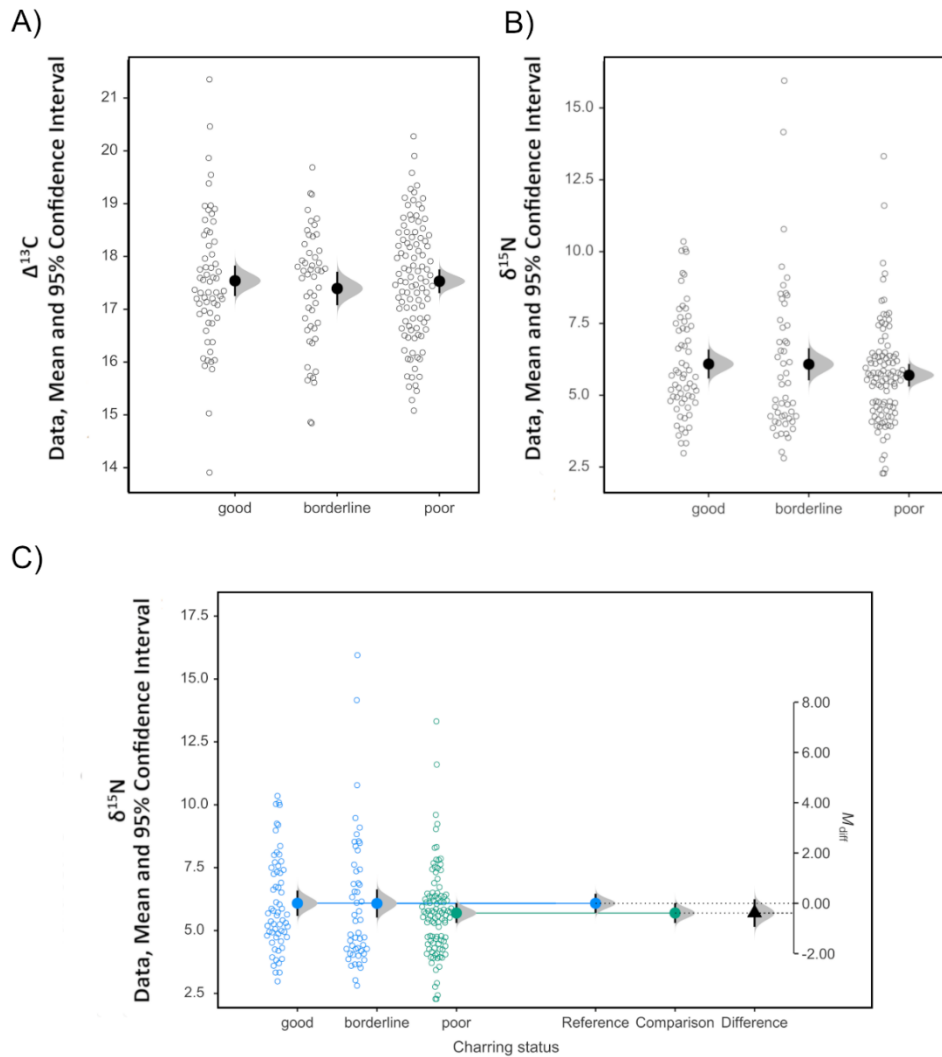
Supplementary Table 7 Continued (Page 2 of 3)

Apiaceae				
<i>Apiaceae</i>			0.06%	15
<i>Apium/Glebionis</i> sp. (Asteraceae)	0.23%	6		
Asteraceae				
<i>Sonchus</i> sp.	0.04%	1		
Asteraceae				
<i>Glebionis</i> sp.			0.05%	12
Brassicaceae			0.02%	5
<i>Brassicaceae siliques</i>			0.24%	64
<i>Bunias</i> sp.			0.13%	35
<i>Capsella bursa-pastoris</i>			0.70%	185
<i>Thlaspi arvense</i>			0.05%	12
Caryophyllaceae				
<i>Cerastium</i> sp.	0.08%	2	0.14%	36
<i>Silene</i> cf. <i>noctiflora</i>	1.91%	49	4.90%	1292
<i>Spergula</i> sp.	0.04%	1		
<i>Stellaria</i> spp.	0.04%	1	0.11%	30
<i>Vaccaria</i> cf. <i>hispanica</i>	0.82%	21	10.54%	2780
<i>Vaccaria</i> sp.	0.55%	14	0.11%	30
Fabaceae				
<i>Ornithopus</i> sp.	0.00%		0.01%	3
<i>Pisum/Vicia</i> spp.	0.08%	2		
<i>Vicia</i> cf. <i>hirsuta</i>			0.39%	104
<i>Vicia</i> sp.			0.22%	59
Malvaceae				
<i>Malva</i> sp.			0.02%	6
Papaveraceae				
cf. <i>Papaver</i> sp.	0.04%	1		
Plantaginaceae				
<i>Kickxia elatine</i>			0.03%	7
<i>Plantago lanceolata</i>	0.27%	7	0.17%	45
<i>Plantago</i> sp.			0.09%	25
Poaceae				
<i>Allium</i> sp.	0.59%	15		
<i>Setaria viridis</i>	0.08%	2	0.14%	38
<i>Setaria pumila</i>			0.03%	8
Rubiaceae				
<i>Galium</i> spp.	2.34%	60	5.90%	1558
Wetland	6.02%	154	41.86%	11045
Cyperaceae			0.13%	33
<i>Carex spicata</i>	0.08%	2		
<i>Carex</i> spp.	1.21%	31	6.66%	1758
Fabaceae				
<i>Medicago/Trifolium</i> spp.	1.21%	31		
<i>Melilotus</i> cf. <i>altissimus</i>	0.08%	2		

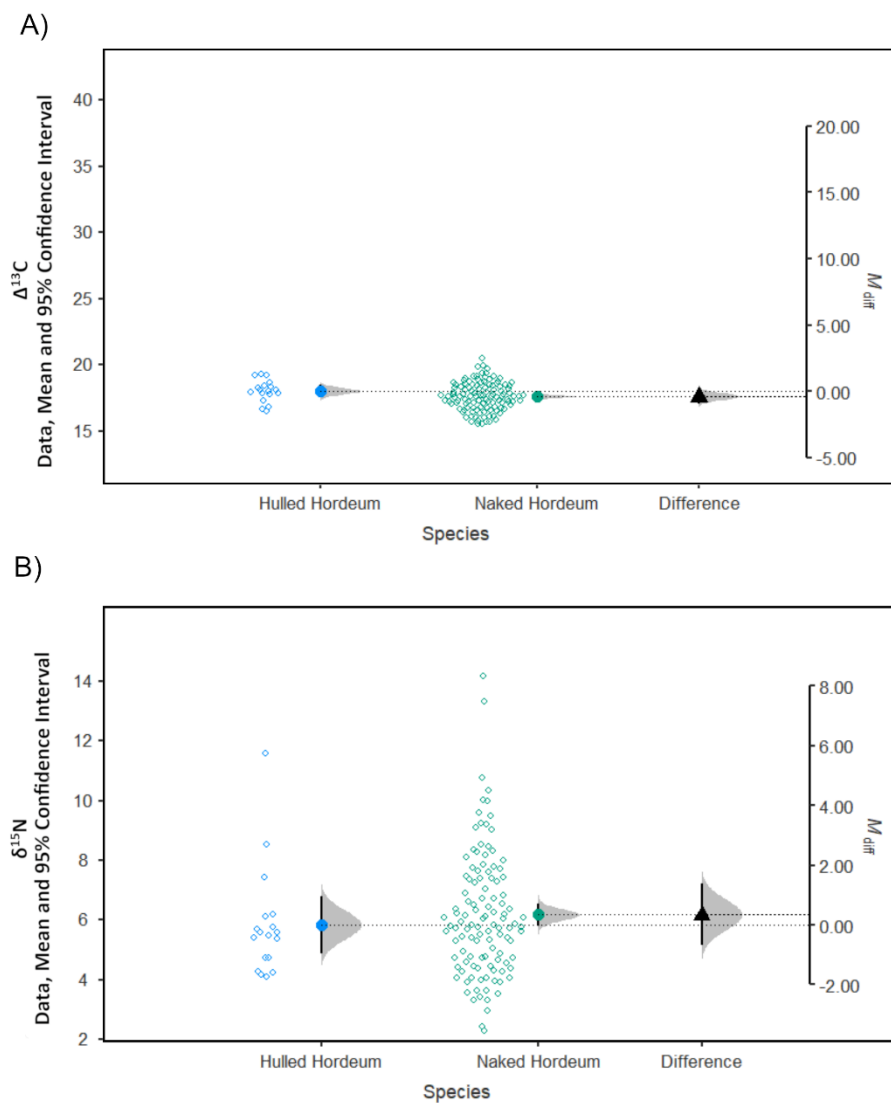
Supplementary Table 7 Continued (Page 3 of 3)

<i>Melilotus</i> sp.	0.59%	15		
<i>Trifolium/Melilotus</i>	0.43%	11	1.07%	283
<i>Trigonella</i> sp.			4.94%	1303
<i>Medicago</i> sp.			0.56%	148
<i>Medicago/Trifolium/Melilotus</i>	1.06%	27	24.32%	6417
Juncaceae				
<i>Juncus</i> sp.			0.01%	3
Poaceae				
<i>Echinochloa colona</i>			0.01%	3
<i>Melica</i> sp.	0.04%	1		
Polygonaceae				
<i>Polygonum</i> spp.	0.82%	21	0.06%	16
<i>Rumex</i> sp.	0.16%	4	0.10%	26
Ranunculaceae				
<i>Ranunculus</i> sp.	0.08%	2		
Rosaceae				
<i>Alchemilla</i> sp.	0.04%	1		
<i>Alchemilla</i> cf. <i>mollis</i>			0.11%	28
<i>Alchemilla/fragaria</i>			3.88%	1024
<i>Potentilla anserina</i>	0.04%	1		
<i>Potentilla</i> sp.	0.20%	5		
<i>Rosa</i> sp.			0.01%	3

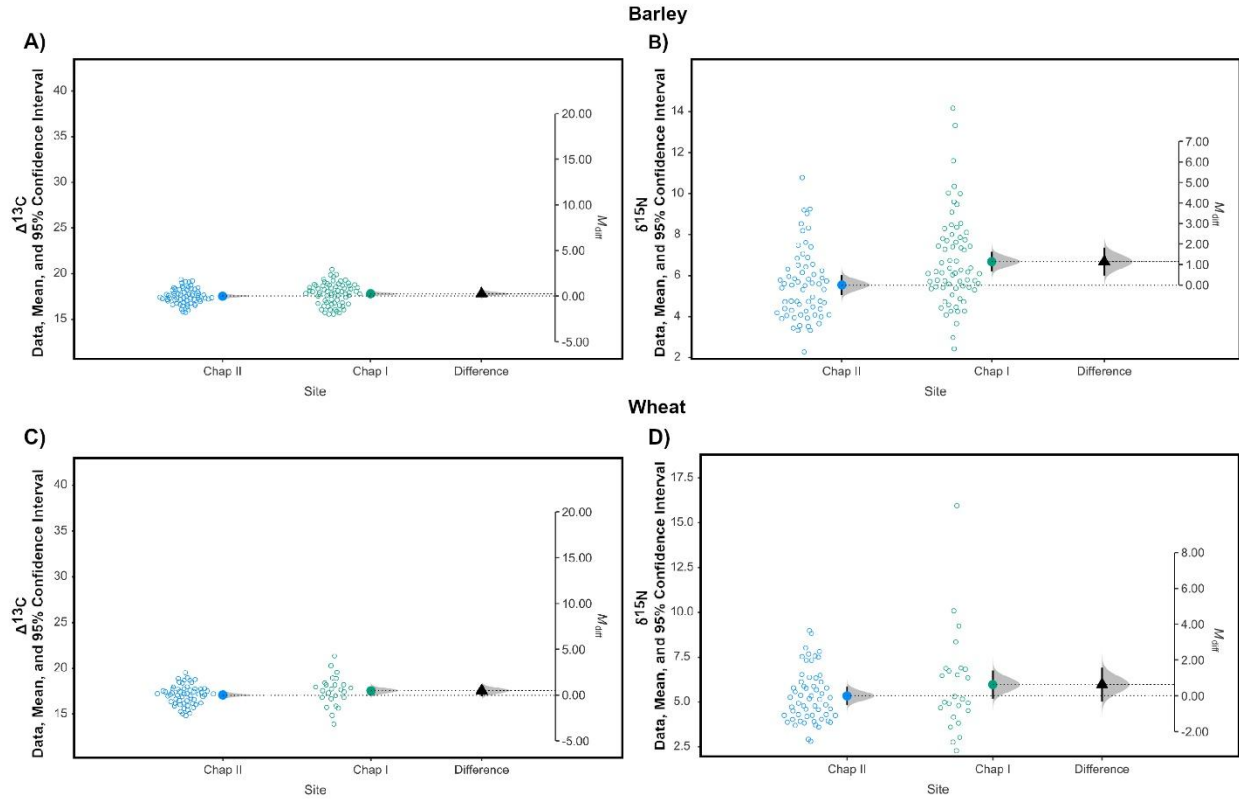
Appendix 3. Chapter 2 Supplementary Figures



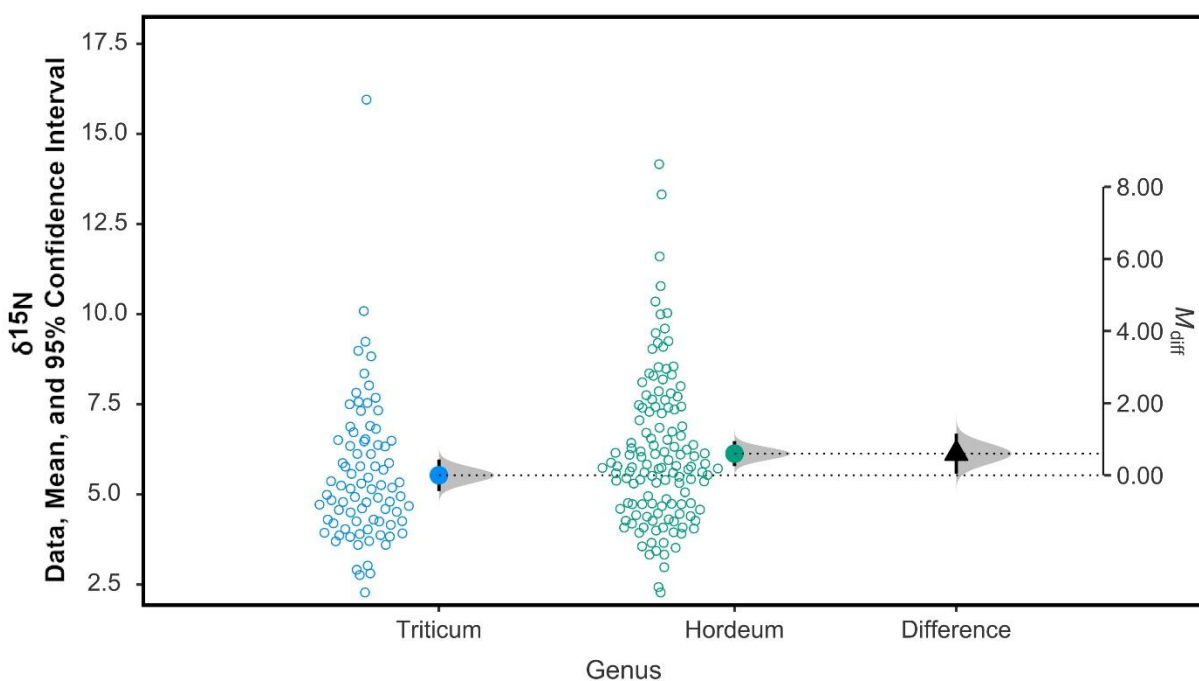
Supplementary Figure 2. Estimation figure of the 95 % CIs of A) $\Delta^{13}\text{C}$ values and B) $\delta^{15}\text{N}$ values of the qualitatively assigned charring status of grains. C) Independent groups contrast comparing the 95 % CIs of $\delta^{15}\text{N}$ values of combined good and borderline (reference) and poor (comparison) grains. The floating axis on the right shows that the best estimate for the mean difference (M_{diff}) between good and poor grains is anywhere between -0.9 and 0.4‰ (Supplementary Table 2).



Supplementary Figure 3. Independent groups contrast comparing the 95 % CIs of A) $\Delta^{13}\text{C}$ and B) $\delta^{15}\text{N}$ of hulled and naked barley. The floating axis on the right shows the best estimate for the mean difference (M_{diff}) between hulled and naked barley. Details found in Supplementary Table 4.



Supplementary Figure 4. Independent groups contrast comparing the 95 % CIs of A) $\Delta^{13}\text{C}$ and B) $\delta^{15}\text{N}$ of barley (naked and hulled combined) and C) $\Delta^{13}\text{C}$ and D) $\delta^{15}\text{N}$ of wheat. The floating axis shows the best estimate for the mean difference (M_{diff}) between hulled and naked barley. Details found in Supplementary Table 5



Supplementary Figure 5. Independent groups contrast comparing the 95 % CIs of $\delta^{15}\text{N}$ of wheat and barley. The floating axis on the right shows that the best estimate for the mean difference (M_{diff}) between wheat and barley is between 0.1 and 1.2. Details found in Supplementary Table 6.

Appendix 4. Chapter 3 Supplementary Tables

Supplementary Table 8. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of Bronze Age wild herbivores from the Bayan-Zhurek Valley. Data from Hermes et al. (2019).

ID	Site	Period	Taxon	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N
4053	Dali	2	red deer	-24.68	9.87	40.09	6.77	6.91
BG0153	Begash	2	red deer	-18.8	7.78	43.74	16.15	3.16
BG0103	Begash	1b	red deer	-19.25	7.54	45.76	17.94	2.98
BG0086	Begash	1b	red deer	-18.26	6.98	45.93	17.23	3.11
BG0079	Begash	1b	red deer	-19.12	6.93	44.93	17.83	2.94
BG0117	Begash	1b	ibex	-18.9	6.85	46.29	18.18	2.97
BG0036	Begash	1a	red deer	-18.77	6.76	44.7	16.64	3.13
BG0176	Begash	2	wild sheep	-18.47	6.63	46.23	16.95	3.18
BG0199	Begash	3a	red deer	-18.37	6.63	41.83	17.07	2.86
BG0056	Begash	1b	red deer	-18.47	6.48	45.28	17.32	3.05
BG0064	Begash	1b	red deer	-18.63	5.99	44.26	17.52	2.95
BG0165	Begash	2	red deer	-19.41	5.95	45.69	16.91	3.15
BG0043	Begash	1b	red deer	-17.97	5.85	44.68	17.64	2.95
BG0285	Begash	3b	red deer	-19.27	5.71	41.97	15.95	3.07
BG0215	Begash	3a	wild sheep	-17.13	5.63	41.71	17.71	2.75
BG0035	Begash	1a	red deer	-19.67	5.57	45.72	17.17	3.11
BG0262	Begash	3b	red deer	-19.39	5.36	42.21	17.24	2.86
BG0236	Begash	3b	red deer	-18.56	5.26	41.64	17.15	2.83
BG0244	Begash	3b	red deer	-19.11	5.24	41.39	17.31	2.79
BG0237	Begash	3b	red deer	-18.92	5.16	41.95	17.54	2.79
BG0152	Begash	2	red deer	-18.58	5.06	45.13	17.53	3
BG0198	Begash	3a	red deer	-19.19	5.05	42.1	17.41	2.82
BG0238	Begash	3b	red deer	-18.73	4.88	41.59	17.56	2.76
BG0067	Begash	1b	red deer	-18.19	4.69	44.48	16.97	3.06
BG0261	Begash	3b	red deer	-18.59	4.61	41.7	17.32	2.81
BG0304_3	Begash	3b	red deer	-19.07	4.42	46.72	17.41	3.13
BG0245	Begash	3b	red deer	-19.03	4.34	42.35	17.22	2.87
BG0277	Begash	3b	red deer	-19.03	4.13	41.24	16.88	2.85
BG0063	Begash	1b	red deer	-20.08	3.84	45.21	17.39	3.03
BG0216	Begash	3a	red deer	-18.45	3.82	41.42	17.72	2.73
4055	Dali	2	ibex	-18.66	3.82	46	16.15	3.32
Average $\delta^{15}\text{N} \pm \text{SD}$								5.7 $\pm$ 1.3
Average $\delta^{15}\text{N}$ - 3‰								2.7
Average $\delta^{15}\text{N}$ - 5‰								0.7
Approximate natural vegetation baselevel								0.7 - 2.7

Supplementary Table 9. Results of macrobotanical analyses for the 2023 excavation at Tasbas.

Sample Information										Fuel residue				Domesticated												Fabaceae																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										
Sample #	Unit	Area	context	Phase	Horizon	Time Period	Volume floated (L)	Wood >2mm ct.	Wood >2mm wt. (g)	Dung >2mm ct.	Dung >2mm wt. (g)																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									

Supplementary Table 9. Continued (Page 2 of 4)

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Supplementary Table 9. Continued (Page 3 of 4)

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Supplementary Table 9. Continued (Page 4 of 4)

Wild												Other												
Rosaceae	Rubiaceae	Solanaceae		Violaceae	Verbenaceae	Unknown																		
Fragaria/Potentilla *	Galium sp.	Solanaceae sp.	Hyoscyamus niger	Hyoscyamus niger *	Violaceae spp.	Veronica sp.	Unidentified Seed	unknown (round with swirl pattern)	plant parts	Unknown tree seed (large)	Nutshell	Awn	palea/lemma	cf. spikelet fork	plant component, unidentified	Thorn	plant Fibers	branch/buds/twigs	catkins	eggshell fragment	ash >2mm wt. (g)	food residue>2mm ct.	food residue>2mm wt. (g)	baked/ashy mudbrick wt. (g)
1				1																				
				3																				
3	1		3	149																				
1			1	1																				
	1																							
																	1							
1																								
1	69		1	31																				
9	2		3	1		1					13			2										
3	1						2																	
5																								
3			2				8	4									4							
3	2		2				5																	
7	6		1	1			11							2										
3	1						10																	
1	3					3	11		10				3					.29g						
1	4																							
	1						6						2	8	1			3			5			
							29																	
14	42				3																			
3	13						11																	
	3		2	1			6													1				
							2																	
	4						2																	
	2						9																	
							7																	
4	2		2				1																	
11							93			3							7	6	9					
7	1						22																	
32			1				24																	
2							2										1							
121	1						14																	
10							18																	
							13										1	16						
15		1	4		2		59																	

Supplementary Table 10. Measurements (mm) of barley (*Hordeum vulgare*) and free-threshing wheat (*Triticum aestivum/durum*) from Tasbas 2023. Empty cells indicate lack of measurement due to an incomplete grain.

Context	Sample #	Taxa	Length	Breadth	Height
11	5	<i>Hordeum vulgare</i>	5.75	4.04	2.76
11	6	<i>Hordeum vulgare</i>	5.69	3.86	3.17
11	6	<i>Hordeum vulgare</i>	5.04	3.63	3.19
17	10	<i>Hordeum vulgare</i>	6.61	3.1	2.68
17	10	<i>Hordeum vulgare</i>		2.67	1.85
20b	13	<i>Hordeum vulgare</i>	5.96	3.96	2.77
20b	13	<i>Hordeum vulgare</i>	4.95	3.11	3.03
20b	13	<i>Hordeum vulgare</i>	4	2.46	2.97
20b	13	<i>Hordeum vulgare</i>	4.5	2.92	2.21
20b	13	<i>Hordeum vulgare</i>	2.64	2.18	1.98
20b	14	<i>Hordeum vulgare</i>	4.57	2.78	2.51
20b	14	<i>Hordeum vulgare</i>	4.06	2.41	2.03
20b	14	<i>Hordeum vulgare</i>	5.45	3.09	2.02
20b	14	<i>Hordeum vulgare</i>	4.6	3.05	2.32
20b	14	<i>Hordeum vulgare</i>	4.57	2.76	2.09
20a	15	<i>Hordeum vulgare</i>	3.79	2.31	1.87
20a	15	<i>Hordeum vulgare</i>	4.89	2.8	2.28
29b	17	<i>Hordeum vulgare</i>	4.58	2.93	2.25
29b	17	<i>Hordeum vulgare</i>	5.7	4.01	3.37
29b	17	<i>Hordeum vulgare</i>	3.34	2.03	1.68
25/29c	18	<i>Hordeum vulgare</i>	6	3.32	2.75
27	20	<i>Hordeum vulgare</i>	5.39	3.15	2.2
27	20	<i>Hordeum vulgare</i>	5.39	2.52	1.83
27	20	<i>Hordeum vulgare</i>	3.39	2.4	1.93
27	20	<i>Hordeum vulgare</i>	5.08	3.03	2.42
27	20	<i>Hordeum vulgare</i>	3.06	1.86	1.46
27	20	<i>Hordeum vulgare</i>	3.22	1.77	1.06
46	33	<i>Hordeum vulgare</i>	4.01	3.45	2.69
46	34	<i>Hordeum vulgare</i>	3.77	2.34	1.5
46	34	<i>Hordeum vulgare</i>	3.19	2.07	2.03
46	34	<i>Hordeum vulgare</i>	3.83	2	1.88
46	34	<i>Hordeum vulgare</i>	3.77	1.93	2.26
46	34	<i>Hordeum vulgare</i>	2.78	1.43	1.52
46	34	<i>Hordeum vulgare</i>	3.5	2.05	1.72
46	34	<i>Hordeum vulgare</i>	4.3	3.5	2.34
46	34	<i>Hordeum vulgare</i>	3.76	2.77	2.18
46	34	<i>Hordeum vulgare</i>	2.42	1.7	1.32
47	35	<i>Hordeum vulgare</i>	4.08	2.81	2.25
47	35	<i>Hordeum vulgare</i>			1.78
48	36	<i>Hordeum vulgare</i>	4.34	3.08	2.32
48	36	<i>Hordeum vulgare</i>	4.03	2.8	2.17
48	36	<i>Hordeum vulgare</i>	3.96	2.97	2.33

Supplementary Table 10. Continued (Page 2 of 3)

48	36	<i>Hordeum vulgare</i>	3.9		1.59
48	36	<i>Hordeum vulgare</i>	3.41	1.87	1.27
48	36	<i>Hordeum vulgare</i>	4.79	2.42	1.66
48	36	<i>Hordeum vulgare</i>	3.9	1.96	1.64
48	36	<i>Hordeum vulgare</i>	4.36	1.93	1.27
48	36	<i>Hordeum vulgare</i>	2.88	1.87	1.5
48	36	<i>Hordeum vulgare</i>	2.81	2.1	1.92
11	5	<i>Triticum aestivum/durum</i>	3.79	3.35	3.06
11	5	<i>Triticum aestivum/durum</i>	5.35	2.93	3.06
11	5	<i>Triticum aestivum/durum</i>	3.67	2.9	2.59
11	5	<i>Triticum aestivum/durum</i>	3.84	2.25	1.84
11	7	<i>Triticum aestivum/durum</i>	2.55	2.18	2.1
11	7	<i>Triticum aestivum/durum</i>	2.7	2.04	1.68
17	10	<i>Triticum aestivum/durum</i>	3.75	2.51	2.61
17b	11	<i>Triticum aestivum/durum</i>	3.97	2.54	1.65
17b	11	<i>Triticum aestivum/durum</i>	4.83	3.35	2.92
21	12	<i>Triticum aestivum/durum</i>	4.6	3.18	3.06
21	12	<i>Triticum aestivum/durum</i>	5.58	3.21	2.53
20b	13	<i>Triticum aestivum/durum</i>	2.86	2.16	1.6
20b	14	<i>Triticum aestivum/durum</i>	4.4	3.06	2.04
20a	15	<i>Triticum aestivum/durum</i>	3.82	3.32	2.98
20a	15	<i>Triticum aestivum/durum</i>	3.45	2.66	2.25
29a	16	<i>Triticum aestivum/durum</i>	4.95	3.67	3.05
29a	16	<i>Triticum aestivum/durum</i>	5.65	3.8	2.97
29a	16	<i>Triticum aestivum/durum</i>	4.39	2.99	2.45
29a	16	<i>Triticum aestivum/durum</i>	3.75	2.83	2.11
25/29c	18	<i>Triticum aestivum/durum</i>	3.96	2.65	2.44
25/29c	18	<i>Triticum aestivum/durum</i>	3.12	2.22	1.87
25/29c	18	<i>Triticum aestivum/durum</i>	4.66	2.62	2.2
25/29c	18	<i>Triticum aestivum/durum</i>	3.83	3.02	2.58
25/29c	18	<i>Triticum aestivum/durum</i>	4.49	3.38	2.7
25/29c	18	<i>Triticum aestivum/durum</i>	4.21	3.69	2.41
25/29c	18	<i>Triticum aestivum/durum</i>	3.24	2.74	2.41
25/29c	18	<i>Triticum aestivum/durum</i>	5.36	3.21	3.17
25/29c	18	<i>Triticum aestivum/durum</i>	4.33	2.15	1.75
29b	19	<i>Triticum aestivum/durum</i>	4.36	2.43	2.15
29b	19	<i>Triticum aestivum/durum</i>	4.24	2.86	2.43
29b	19	<i>Triticum aestivum/durum</i>	4.35	2.64	2.55
29b	19	<i>Triticum aestivum/durum</i>	4.45	2.57	
29b	19	<i>Triticum aestivum/durum</i>	4.86	3.14	2.62
29b	19	<i>Triticum aestivum/durum</i>	5.62	3.41	3.19
29b	19	<i>Triticum aestivum/durum</i>	5.39	3.51	3.03
32a	25	<i>Triticum aestivum/durum</i>	2.42	3.14	1.97
32a	25	<i>Triticum aestivum/durum</i>	2.91	2.42	1.75
32a	25	<i>Triticum aestivum/durum</i>	2.71	2.49	2.35
36	28	<i>Triticum aestivum/durum</i>	2.96	2.22	2.2

Supplementary Table 10. Continued (Page 3 of 3)

48	36	<i>Triticum aestivum/durum</i>	3.69	2.15	1.89
48	36	<i>Triticum aestivum/durum</i>	3.33	2.24	1.7
48	36	<i>Triticum aestivum/durum</i>	3.4	2.72	2.31
48	36	<i>Triticum aestivum/durum</i>	2.55	1.75	1.86
48	36	<i>Triticum aestivum/durum</i>	2.79	2.09	1.64

Supplementary Table 11. Measurements (mm) of broomcorn millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) from Tasbas 2023.

Context	Sample #	Taxa	Length	Breadth	embryo length	embryo breadth
32a	25	<i>Panicum miliaceum</i>	1.17	1.33	0.72	0.65
32a	25	<i>Panicum miliaceum</i>	1.32	1.17	0.43	0.54
32a	25	<i>Panicum miliaceum</i>	1.75	1.66	0.74	0.76
32a	25	<i>Panicum miliaceum</i>	1.63	1.5	0.79	0.83
32a	25	<i>Panicum miliaceum</i>	1.29	0.45	0.46	0.79
32a	25	<i>Panicum miliaceum</i>	1.58	1.58	0.47	0.8
32a	25	<i>Panicum miliaceum</i>	1.14	1.36	0.56	0.77
32a	25	<i>Panicum miliaceum</i>	1.63	1.45	0.46	0.93
40	29	<i>Panicum miliaceum</i>	1.39	1.28	0.76	0.81
40	29	<i>Panicum miliaceum</i>	1.54	1.07	0.73	0.52
40	29	<i>Panicum miliaceum</i>	1.47	1.45	0.9	0.84
40	29	<i>Panicum miliaceum</i>	1.88	1.63	1.24	0.87
40	29	<i>Panicum miliaceum</i>	1.75	1.63	1.04	0.75
40	29	<i>Panicum miliaceum</i>	1.71	1.57	0.87	0.72
40	29	<i>Panicum miliaceum</i>	1.63	1.29	0.61	0.69
40	29	<i>Panicum miliaceum</i>	1.62	1.5	0.43	0.61
40	29	<i>Panicum miliaceum</i>	1.66	1.52	1.15	1.15
40	29	<i>Panicum miliaceum</i>	1.66	1.54	1.03	1.15
40	29	<i>Panicum miliaceum</i>	1.9	1.7	1.55	1.34
40	29	<i>Panicum miliaceum</i>	1.26	1.35	0.74	0.98
40	29	<i>Panicum miliaceum</i>	2	1.94	0.92	0.71
40	29	<i>Panicum miliaceum</i>	1.44	1.27	0.66	0.68
40	29	<i>Panicum miliaceum</i>	1.77	1.66	0.76	0.61
40	29	<i>Panicum miliaceum</i>	1.57	1.3	0.68	0.43
40	29	<i>Panicum miliaceum</i>	1.25	1.09	0.73	0.49
40	29	<i>Panicum miliaceum</i>	1.92	1.83	0.79	1.1
40	29	<i>Panicum miliaceum</i>	1.57	1.57	0.77	0.57
40	29	<i>Panicum miliaceum</i>	1.86	1.44	0.72	0.68
40	29	<i>Panicum miliaceum</i>	1.69	1.38	0.84	0.53
40	29	<i>Panicum miliaceum</i>	1.7	1.36	0.78	0.72
40	29	<i>Panicum miliaceum</i>	1.51	1.31	0.72	0.7
40	29	<i>Panicum miliaceum</i>	1.74	1.22	0.79	0.62
40	29	<i>Panicum miliaceum</i>	2.09	1.79	1.41	0.96

Supplementary Table 11. Continued (Page 2 of 4)

40	29	<i>Panicum miliaceum</i>	1.62	1.36	0.99	0.57
40	29	<i>Panicum miliaceum</i>	1.45	1.33	0.56	0.59
40	29	<i>Panicum miliaceum</i>	1.88	1.55	0.63	0.62
40	29	<i>Panicum miliaceum</i>	1.35	1.39	0.6	0.49
40	29	<i>Panicum miliaceum</i>	1.44	1.34	0.72	0.54
40	29	<i>Panicum miliaceum</i>	1.48	1.21	0.59	0.62
40	29	<i>Panicum miliaceum</i>	1.46	1.29	0.62	0.67
40	29	<i>Panicum miliaceum</i>	1.8	1.38	0.79	0.46
40	29	<i>Panicum miliaceum</i>	1.51	1.41	0.57	0.65
40	29	<i>Panicum miliaceum</i>	1.64	1.53	0.48	0.79
40	29	<i>Panicum miliaceum</i>	1.83	1.51	0.6	0.68
40	29	<i>Panicum miliaceum</i>	1.65	1.39	0.62	0.71
40	29	<i>Panicum miliaceum</i>	1.56	1.31	0.51	0.52
40	29	<i>Panicum miliaceum</i>	1.61	1.6	0.74	0.91
40	29	<i>Panicum miliaceum</i>	1.8	1.46	0.45	0.7
40	29	<i>Panicum miliaceum</i>	2.06	1.33	0.88	0.59
40	29	<i>Panicum miliaceum</i>	1.89	1.49	0.85	0.55
40	29	<i>Panicum miliaceum</i>	1.54	1.5	0.85	0.76
40	29	<i>Panicum miliaceum</i>	1.59	1.4	0.69	0.81
40	29	<i>Panicum miliaceum</i>	1.45	1.4	0.58	0.77
40	29	<i>Panicum miliaceum</i>	1.35	1.33	0.71	0.69
40	29	<i>Panicum miliaceum</i>	1.67	1.41	0.84	0.72
40	29	<i>Panicum miliaceum</i>	1.29	1.25	0.67	0.58
40	29	<i>Panicum miliaceum</i>	1.57	1.46	0.86	0.53
40	29	<i>Panicum miliaceum</i>	1.47	1.27	0.46	0.7
40	29	<i>Panicum miliaceum</i>	1.38	1.22	0.68	0.72
40	29	<i>Panicum miliaceum</i>	1.58	1.2	0.84	0.76
40	29	<i>Panicum miliaceum</i>	1.74	1.08	0.61	0.62
40	29	<i>Panicum miliaceum</i>	1.31	1.37	0.74	0.8
40	29	<i>Panicum miliaceum</i>	1.42	1.46	0.75	0.7
40	29	<i>Panicum miliaceum</i>	1.51	1.33	0.73	0.6
40	29	<i>Panicum miliaceum</i>	1.11	1.41	0.43	0.72
40	29	<i>Panicum miliaceum</i>	1.37	1.14	0.68	0.69
40	29	<i>Panicum miliaceum</i>	1.72	1.4	0.84	0.83
40	29	<i>Panicum miliaceum</i>	1.34	1.18	0.69	0.77
40	29	<i>Panicum miliaceum</i>	1.49	1.63	0.62	0.72
40	29	<i>Panicum miliaceum</i>	1.5	1.36	0.84	0.59
40	29	<i>Panicum miliaceum</i>	1.61	1.47	0.75	0.77
40	29	<i>Panicum miliaceum</i>	1.29	1.19	0.72	0.65
40	29	<i>Panicum miliaceum</i>	1.62	1.22	0.98	0.69
40	29	<i>Panicum miliaceum</i>	1.46	1.32	0.86	0.7
40	29	<i>Panicum miliaceum</i>	1.49	1.58	0.96	0.74
40	29	<i>Panicum miliaceum</i>	1.34	1.18	0.63	0.63

Supplementary Table 11. Continued (Page 3 of 4)

40	29	<i>Panicum miliaceum</i>	1.77	1.48	0.66	0.94
40	29	<i>Panicum miliaceum</i>	1.05	1.04	0.5	0.73
40	29	<i>Panicum miliaceum</i>	1.42	1.3	0.68	0.556
40	29	<i>Panicum miliaceum</i>	1.52	1.5	0.62	0.88
40	29	<i>Panicum miliaceum</i>	1.44	1.32	0.55	0.77
40	29	<i>Panicum miliaceum</i>	1.08	1.17	0.59	0.5
40	29	<i>Panicum miliaceum</i>	1.29	1.61	0.8	0.79
40	29	<i>Panicum miliaceum</i>	1.37	1.28	0.51	0.7
40	29	<i>Panicum miliaceum</i>	1.53	1.39	0.75	0.76
40	29	<i>Panicum miliaceum</i>	1.8	1.6	0.61	0.76
40	29	<i>Panicum miliaceum</i>	1.65	1.65	0.74	0.75
40	29	<i>Panicum miliaceum</i>	1.33	1.21	0.54	0.65
40	29	<i>Panicum miliaceum</i>	1.34	1.18	0.59	0.7
40	29	<i>Panicum miliaceum</i>	1.37	1.4	0.75	0.56
40	29	<i>Panicum miliaceum</i>	1.16	1.3	0.79	0.67
40	29	<i>Panicum miliaceum</i>	1.31	1.3	0.65	0.66
40	29	<i>Panicum miliaceum</i>	1.39	1.16	0.74	0.67
40	29	<i>Panicum miliaceum</i>	1.5	1.45	0.56	0.48
40	29	<i>Panicum miliaceum</i>	1.02	1.31	0.35	0.74
40	29	<i>Panicum miliaceum</i>	1.3	1.37	0.6	0.87
40	29	<i>Panicum miliaceum</i>	1.2	1.12	0.71	0.69
40	29	<i>Panicum miliaceum</i>	1.22	1.24	0.66	0.59
40	29	<i>Panicum miliaceum</i>	1.5	1.19	0.66	0.55
41	30	<i>Panicum miliaceum</i>	1.96	1.6	0.68	0.78
41	30	<i>Panicum miliaceum</i>	1.63	1.35	0.79	0.68
41	30	<i>Panicum miliaceum</i>	1.81	1.57	0.93	0.92
41	30	<i>Panicum miliaceum</i>	1.79	1.75	0.92	0.8
41	30	<i>Panicum miliaceum</i>	1.73	1.64	0.76	0.78
41	30	<i>Panicum miliaceum</i>	1.27	1.07	0.51	0.61
41	30	<i>Panicum miliaceum</i>	1.39	1.2	0.56	0.75
46	34	<i>Panicum miliaceum</i>	1.66	1.59	0.96	0.93
46	34	<i>Panicum miliaceum</i>	1.42	1.61	0.78	0.97
48	36	<i>Panicum miliaceum</i>	1.69	1.29	0.89	0.68
48	36	<i>Panicum miliaceum</i>	1.97	1.71	0.99	0.85
48	36	<i>Panicum miliaceum</i>	1.92	1.63	1.07	0.81
17	10	<i>Setaria italica</i>	3.52	3.27	0.86	1.68
40	29	<i>Setaria italica</i>	1.52	1.26	0.75	0.74
40	29	<i>Setaria italica</i>	1.61	1.44	1.01	0.62
40	29	<i>Setaria italica</i>	1.69	1.65	1.03	0.72
40	29	<i>Setaria italica</i>	1.18	1.25	0.82	0.72
40	29	<i>Setaria italica</i>	1.33	1.22	0.94	0.52
40	29	<i>Setaria italica</i>	1.15	1.18	0.71	0.36
40	29	<i>Setaria italica</i>	1.09	0.94	0.73	0.45

Supplementary Table 11. Continued (Page 4 of 4)

40	29	<i>Setaria italica</i>	1.77	1.49	1.14	0.73
40	29	<i>Setaria italica</i>	1.4	0.97	1.01	0.59
40	29	<i>Setaria italica</i>	1.38	1.27	1.06	0.56
40	29	<i>Setaria italica</i>	1.28	1	0.9	0.48
40	29	<i>Setaria italica</i>	1.68	1.07	0.89	0.62
40	29	<i>Setaria italica</i>	1.25	1.21	0.6	0.65
40	29	<i>Setaria italica</i>	1.32	1.3	0.8	0.37
40	29	<i>Setaria italica</i>	1.41	0.9	1.02	0.46
40	29	<i>Setaria italica</i>	1.11	0.92	0.83	0.37
40	29	<i>Setaria italica</i>	1.56	1.16	1.08	0.7
40	29	<i>Setaria italica</i>	1.16	0.89	0.81	0.51
40	29	<i>Setaria italica</i>	1.23	1.01	0.93	0.51
40	29	<i>Setaria italica</i>	1.49	1.21	0.92	0.6
40	29	<i>Setaria italica</i>	1.14	1.21	1	0.62
40	29	<i>Setaria italica</i>	1.9	1.47	1.14	0.51
40	29	<i>Setaria italica</i>	1.56	1.44	1.12	0.58
40	29	<i>Setaria italica</i>	1.39	0.95	1	0.46
40	29	<i>Setaria italica</i>	1.48	1.16	1.13	0.65
40	29	<i>Setaria italica</i>	1.35	1.29	0.52	0.61
40	29	<i>Setaria italica</i>	1.15	1.08	0.95	0.45
40	29	<i>Setaria italica</i>	1.45	1.12	1.09	0.67
40	29	<i>Setaria italica</i>	1.5	1.21	1.09	0.86
40	29	<i>Setaria italica</i>	1.34	1.26	0.87	0.59
40	29	<i>Setaria italica</i>	1.58	1.1	0.83	0.55

Supplementary Table 12. Analysis of confidence intervals, displayed in Supplementary Figure 7, between qualitatively assigned charring condition and $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wheat and barley grains.

Outcome variable	Condition	M	95 CI		Mdn	s	n
			LL	UL			
$\delta^{15}\text{N}$	good	6.1	5.3	6.8	5.5	2.7	49
	borderline	5.9	4.7	7.1	5.5	2.7	19
	poor	5.9	4.9	6.9	5.5	2.5	27
$\Delta^{13}\text{C}$	good	17.4	17.0	17.8	17.5	1.6	49
	borderline	17.7	17.0	18.4	17.6	1.5	19
	poor	17.7	17.2	18.3	17.8	1.4	27

Supplementary Table 13. Results of stable isotope analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for domesticated taxa and wild taxa from Tasbas.

LABID	year	Unit	Level	Time	Phase	Area	context	Sample	Date	Taxon	count	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N	$\Delta^{13}\text{C}$
TB11F14_H1	2011	2	L/A	Late Iron Age	2a	16c	106	14	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.6	11.2	59.7	6.8	8.8	17.5
TB11F14_H2	2011	2	L/A	Late Iron Age	2a	16c	106	14	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.1	3.5	67.6	3.8	18.0	18.0
TB11F14_H3	2011	2	L/A	Late Iron Age	2a	16c	106	14	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-22.3	2.9	62.0	4.5	13.9	16.1
TB11F14_H4	2011	2	L/A	Late Iron Age	2a	16c	106	14	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.6	3.9	58.7	4.0	14.7	17.5
TB11F17_H10	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.8	7.1	56.6	6.0	9.5	17.7
TB11F17_H11	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.6	6.1	57.3	8.1	7.1	17.5
TB11F17_H1avg	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.0	3.4	60.3	4.2	14.3	16.8
TB11F17_H2avg	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-22.9	7.4	62.4	5.3	11.8	16.8
TB11F17_H4	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.6	5.7	54.8	3.4	15.9	17.5
TB11F17_H5	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.0	2.1	56.2	4.5	12.5	16.9
TB11F17_H7avg	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.3	3.9	55.5	4.0	14.2	17.2
TB11F17_H8	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.0	11.8	60.0	6.7	8.9	16.9
TB11F17_H9	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-25.1	3.8	62.1	4.0	15.6	19.1
TB11F17_P1	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Pisum sativum</i>	1	-24.6	1.5	54.8	7.3	7.5	18.6
TB11F19_H11	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.2	2.5	61.6	3.4	18.2	17.1
TB11F19_H12	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-21.2	9.9	61.1	3.1	20.0	15.0
TB11F19_H2	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.8	5.0	63.4	3.4	18.6	18.8
TB11F19_H3	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-25.2	7.4	61.8	5.0	12.5	19.2
TB11F19_H4	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.8	6.3	66.2	4.4	15.2	18.8
TB11F19_H6avg	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-22.3	4.9	57.2	4.6	12.5	16.2
TB11F19_H7	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-22.6	4.0	58.4	4.6	12.6	16.5
TB11F19_H8	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-25.1	10.4	58.2	5.1	11.3	19.1
TB11F19_H9avg	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-22.1	8.9	53.6	4.7	11.5	16.0
TB11F19_P1	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Pisum</i>	1	-24.1	1.9	60.8	8.6	7.0	18.0
TB11F19_P2	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Pisum</i>	1	-23.6	1.8	60.7	6.9	8.8	17.5
TB11F19_P3	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Pisum</i>	1	-23.8	3.5	60.9	5.8	10.6	17.7
TB11F19_P4	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Pisum</i>	1	-23.4	1.0	62.5	6.1	10.2	17.3
TB11F19_P5	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Pisum</i>	1	-24.5	2.4	61.4	8.9	6.9	18.4
TB11F19_T1	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Triticum aestivum</i>	1	-21.8	4.7	61.0	5.1	11.9	15.6
TB11F22_H1	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-21.4	6.9	56.0	4.9	11.4	15.2
TB11F22_H10	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-20.7	5.9	52.6	4.4	12.0	14.5
TB11F22_H11	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-20.9	10.6	57.7	7.2	8.0	14.7

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TB11F22_H2	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-21.0	6.9	54.7	9.1	6.0	14.8
TB11F22_H3	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.5	8.8	56.4	7.9	7.2	17.4
TB11F22_H4	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.9	8.0	57.9	5.8	10.0	17.8
TB11F22_H5	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.8	3.3	55.5	3.9	14.1	18.8
TB11F22_H8	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-21.1	7.0	54.7	5.1	10.7	14.9
TB11F22_H9.avg	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.0	6.2	66.5	2.6	25.6	18.0
TB11F22_P1	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Pisum</i>	1	-22.8	2.7	56.4	5.3	10.6	16.6
TB11F22_P2	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Pisum</i>	1	-23.4	1.5	56.1	6.3	9.0	17.3
TB11F22_P3	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Pisum</i>	1	-23.9	1.3	64.4	7.8	8.2	17.9
TB11F22_P4	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Pisum</i>	1	-24.1	3.9	56.7	8.0	7.1	18.0
TB11F22_P5	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Pisum</i>	1	-25.2	1.8	62.2	5.2	11.9	19.1
TB11F22_I1	2011	NA	LBA	Late Bronze Age	2a	NA	109B	22	1400-1200 cal BCE	<i>Triticum aestivum</i>	1	-22.1	13.0	55.6	9.7	5.7	16.0
TB11F23_H1	2011	NA	LBA	Late Bronze Age	2a	NA	123	23	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.1	7.6	62.8	5.8	10.9	17.0
TB11F23_H2	2011	NA	LBA	Late Bronze Age	2a	NA	123	23	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.5	5.8	58.3	5.1	11.5	18.4
TB11F23_H3	2011	NA	LBA	Late Bronze Age	2a	NA	123	23	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.9	7.9	63.3	4.4	14.5	17.8
TB11F23_H6	2011	NA	LBA	Late Bronze Age	2a	NA	123	23	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.7	6.6	49.0	2.7	18.5	18.7
TB11F24_H1	2011	NA	LBA	Late Bronze Age	2a	NA	129	24	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.0	8.2	67.2	4.2	16.0	16.9
TB11F24_H2	2011	NA	LBA	Late Bronze Age	2a	NA	129	24	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.1	9.5	63.1	4.7	13.5	18.0
TB11F24_H3	2011	NA	LBA	Late Bronze Age	2a	NA	129	24	1400-1200 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.5	9.4	61.1	6.1	10.0	18.5
TB11F27_H1	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-24.3	3.1	70.1	2.5	28.3	18.3
TB11F27_H2	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-22.5	6.9	63.1	3.2	19.8	16.4
TB11F27_H3	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.3	8.5	64.3	4.0	16.1	17.2
TB11F27_H4	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-23.0	11.8	55.8	11.5	4.9	16.9
TB11F27_H5	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-19.4	9.0	61.6	5.1	12.0	13.2
TB11F27_H8	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Hordeum vulgare</i> var. <i>nudum</i>	1	-22.9	8.9	56.4	12.8	4.4	16.8
TB23F13_H2	2023	OP4	EIA	Early Iron Age	4	NA	20b	13	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-25.0	6.6	58.3	3.8	15.4	19.0
TB23F13_H3	2023	OP4	EIA	Early Iron Age	4	NA	20b	13	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-29.5	11.7	55.1	9.6	5.7	23.7
TB23F16_T1avg	2023	OP4	EIA	Early Iron Age	4	B/C 7,8	29a	16	789-551 cal BCE	<i>Triticum aestivum</i>	1	-24.3	10.4	63.4	4.7	13.6	18.3
TB23F16_I2	2023	OP4	EIA	Early Iron Age	4	B/C 7,8	29a	16	789-551 cal BCE	<i>Triticum aestivum</i>	1	-23.9	3.2	60.6	3.1	19.4	17.8
TB23F18_I1	2023	OP4	EIA	Early Iron Age	4	B 7	25/29c	18	789-551 cal BCE	<i>Triticum aestivum</i>	1	-24.4	4.5	55.5	5.1	10.9	18.3
TB23F18_I2	2023	OP4	EIA	Early Iron Age	4	B 7	25/29c	18	789-551 cal BCE	<i>Triticum aestivum</i>	1	-25.6	4.0	19.5	1.1	17.2	19.5
TB23F18_I3	2023	OP4	EIA	Early Iron Age	4	B 7	25/29c	18	789-551 cal BCE	<i>Triticum aestivum</i>	1	-25.6	3.2	21.7	1.2	17.5	19.5
TB23F19_I1	2023	OP4	EIA	Early Iron Age	4	B 8	29b	19	789-551 cal BCE	<i>Triticum aestivum</i>	1	-23.0	3.1	61.4	3.7	16.7	16.8
TB23F19_I2	2023	OP4	EIA	Early Iron Age	4	B 8	29b	19	789-551 cal BCE	<i>Triticum aestivum</i>	1	-23.5	4.3	53.6	4.3	12.3	17.4

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TB23F20_H1	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-24.0	3.8	61.5	4.3	14.3	17.9
TB23F20_H2	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-23.6	5.5	65.1	3.2	20.2	17.5
TB23F20_H3	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-22.8	1.3	66.1	3.2	20.5	16.6
TB23F20_H4	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-23.0	5.5	61.4	5.9	10.4	16.9
TB23F20_H5	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-22.9	4.7	61.8	5.4	11.4	16.8
TB23F20_T1	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	789-551 cal BCE	<i>Triticum aestivum</i>	1	-23.8	5.4	64.6	4.0	16.2	17.8
TB23F21_H5	2023	OP4	EIA	Early Iron Age	4	B 7.12	25	21	789-551 cal BCE	<i>Hordeum vulgare</i>	1	-27.1	4.6	52.9	2.6	20.6	21.2
TB23F25_T1	2023	OP2	MBA	Middle Bronze Age	1	NA	32a	25	1950-1775 BCE	<i>Hordeum vulgare</i>	1	-23.2	4.5	57.5	4.0	14.2	17.1
TB23F25_T2	2023	OP2	MBA	Middle Bronze Age	1	NA	32a	25	1950-1775 BCE	<i>Triticum aestivum</i>	1	-23.1	5.0	61.9	4.6	13.5	17.0
TB23F31_H1avg	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-22.9	4.8	60.4	1.8	38.5	16.8
TB23F31_H2	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-24.2	5.5	58.9	5.4	10.9	18.2
TB23F31_H3	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-23.3	6.1	56.9	4.6	12.2	17.2
TB23F31_H6	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-24.1	2.7	69.6	3.2	21.7	18.1
TB23F31_T1avg	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Triticum aestivum</i>	1	-22.1	3.4	63.1	5.3	11.8	16.0
TB23F31_T2	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Triticum aestivum</i>	1	-23.9	7.1	57.6	4.6	12.5	17.9
TB23F31_T3avg	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Triticum aestivum</i>	1	-23.9	7.2	61.8	4.9	12.7	17.8
TB23F31_T4	2023	OP2	LBA	Late Bronze Age	2b	NA	35C	31	1212-1055 BCE	<i>Triticum aestivum</i>	1	-22.8	2.7	59.9	4.2	14.4	16.7
TB23F34_H1	2023	OP2	FBA	Final Bronze Age	2b	D 9	46	34	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-24.2	5.0	49.0	2.9	17.2	18.1
TB23F34_H2	2023	OP2	FBA	Final Bronze Age	2b	D 9	46	34	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-23.8	4.9	69.7	2.9	24.2	17.8
TB23F34_H3	2023	OP2	FBA	Final Bronze Age	2b	D 9	46	34	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-26.7	5.3	59.6	2.5	24.0	20.8
TB23F34_H4	2023	OP2	FBA	Final Bronze Age	2b	D 9	46	34	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-26.0	3.0	48.3	2.6	18.5	20.0
TB23F34_H5	2023	OP2	FBA	Final Bronze Age	2b	D 9	46	34	1212-1055 BCE	<i>Hordeum vulgare</i>	1	-24.9	4.9	62.7	2.9	21.6	18.9
TB23F34_T1avg	2023	OP2	FBA	Final Bronze Age	2b	D 9	46	34	1212-1055 BCE	<i>Triticum aestivum</i>	1	-23.8	4.6	66.4	2.8	24.0	17.7
TB23F36_H1	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-23.7	4.9	59.5	6.1	9.7	17.6
TB23F36_H10avg	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-24.1	5.4	55.6	5.2	10.7	18.0
TB23F36_H2	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-22.7	5.7	52.3	3.1	17.0	16.6
TB23F36_H3	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-24.1	8.2	58.9	5.3	11.1	18.0
TB23F36_H4	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-23.7	7.4	59.9	6.2	9.7	17.6
TB23F36_H5	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-24.8	8.1	59.4	5.8	10.2	18.7
TB23F36_H6	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-22.6	6.9	64.0	5.0	12.8	16.4
TB23F36_H7avg	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-25.9	9.7	57.6	6.0	9.6	19.9
TB23F36_H8	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-25.8	7.7	64.2	5.0	12.8	19.8
TB23F36_H8avg	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Hordeum vulgare</i>	1	-25.4	8.4	60.5	4.0	15.3	19.3
TB23F36_T1(6avg)	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Triticum aestivum</i>	1	-23.7	4.6	62.4	4.0	15.7	17.6

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TB23F36_T1(a)	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Triticum aestivum</i>	1	-23.9	4.5	60.1	3.7	16.3	17.8
TB23F36_I2	2023	OP2	FBA	Final Bronze Age	2b	H 8	48	36	1255 - 1055 BCE	<i>Triticum aestivum</i>	1	-22.7	2.5	67.6	3.8	17.7	16.5
TB23F36_I2(7)	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Triticum aestivum</i>	1	-22.6	2.1	63.6	3.9	16.3	16.4
TB23F36_I3	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Triticum aestivum</i>	1	-23.5	2.2	67.1	3.8	17.5	17.4
TB23F36_I4	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Triticum aestivum</i>	1	-23.4	3.2	59.3	2.7	21.8	17.3
TB23F36_I5	2023	OP2	FBA	Final Bronze Age	2b	H 7	48	36	1255-1055 BCE	<i>Triticum aestivum</i>	1	-22.7	3.9	61.4	4.3	14.2	16.6
TB11F14_CH1	2011	2	L/A	Late Iron Age	2a	16c	106	14	1400-1200 cal BCE	<i>Chenopodium album</i>	17	-25.0	12.0	60.4	4.6	13.1	19.0
TB11F14_TR1	2011	2	L/A	Late Iron Age	2a	16c	106	14	1400-1200 cal BCE	<i>Trigonella</i>	6	-22.5	1.9	61.1	8.6	7.1	16.4
TB11F17_CH_AVG	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Chenopodium album</i>	42	-26.0	9.8	60.6	4.0	15.1	20.0
TB11F17_TR1	2011	2	LBA	Late Bronze Age	2a	16 b and c	109	17	1400-1200 cal BCE	<i>Trigonella</i>	20	-22.8	3.7	60.2	9.4	6.4	16.6
TB11F19_CH_AVG	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Chenopodium album</i>	32	-27.1	11.0	60.6	4.3	14.0	21.2
TB11F19_G1	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Galium</i>	12	-26.2	9.9	56.8	4.6	12.4	20.2
TB11F19_HW1	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Hordeum wild?</i>	2	NA	10.0	33.4	7.6	4.4	NA
TB11F19_S1	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Stipa</i>	22	-21.6	6.5	58.5	8.3	7.0	15.4
TB11F19_S1	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Stipa</i>	22	-22.5	6.9	57.0	8.2	6.9	16.4
TB11F19_TR1	2011	2	LBA	Late Bronze Age	2a	16 d	110	19	1400-1200 cal BCE	<i>Trigonella</i>	15	-23.2	3.4	61.6	8.6	7.1	17.1
TB11F24_CH1	2011	NA	LBA	Late Bronze Age	2a	NA	129	24	1400-1200 cal BCE	<i>Chenopodium album</i>	19	-19.4	9.5	55.5	3.4	16.5	13.1
TB11F24_G1	2011	NA	LBA	Late Bronze Age	2a	NA	129	24	1400-1200 cal BCE	<i>Galium</i>	13	-25.0	4.0	60.6	4.3	14.2	19.0
TB11F24_TR_AVG	2011	NA	LBA	Late Bronze Age	2a	NA	129	24	1400-1200 cal BCE	<i>Trigonella</i>	17	-23.3	3.2	62.6	9.0	6.9	17.2
TB11F27_CH1	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Chenopodium album</i>	30	-22.7	11.1	59.5	3.4	17.6	16.5
TB11F27_TR1	2011	NA	LBA	Late Bronze Age	2a	NA	126	27	1370-1127 cal BCE	<i>Trigonella</i>	13	-22.3	3.7	61.2	8.0	7.6	16.2
TB23F20_G1	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	778-551 cal BCE	<i>Galium</i>	5	-23.9	NA	87.3	5.4	16.3	17.9
TB23F20_G2	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	778-551 cal BCE	<i>Galium</i>	5	-24.9	4.5	57.5	4.2	13.6	18.9
TB23F20_G2	2023	OP4	EIA	Early Iron Age	4	A 7/8	27	20	778-551 cal BCE	<i>Galium</i>	5	-24.8	4.6	54.1	3.8	14.1	18.8
TB23F21_M7/M1	2023	OP4	EIA	Early Iron Age	4	B 7,8	25	21	778-551 cal BCE	<i>medicago/trigonella/mellilotus</i>	15	-23.3	2.5	56.9	8.6	6.6	17.2
TB23F31_CH1	2023	OP2	LBA	Late Bronze Age	3	NA	35C	31	1212-1055 cal BCE	<i>Chenopodium album</i>	30	-26.8	9.1	56.7	4.0	14.2	20.9
TB23F36_CH1	2023	OP2	FBA	Final Bronze Age	3	H 7	48	36	1255-1055 cal BCE	<i>Chenopodium album</i>	30	-26.3	10.6	55.4	4.6	12.0	20.4
TB23F36_M7/M	2023	OP2	FBA	Final Bronze Age	3	H 7	48	36	1255-1055 cal BCE	<i>medicago/trigonella/mellilotus</i>	13	-24.1	3.9	54.8	8.3	6.6	18.0

Supplementary Table 14. Results of confidence interval comparisons of the mean, displayed in Supplementary Figures 4 and 5, of $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of free-threshing wheat and barley grains through time from Tasbas.

Mean Difference						
Taxa	Outcome variable	Site Effect	M	95% CI		n
				LL	UL	
Barley	$\Delta^{13}\text{C}$	LBA	17.1	16.7	17.5	44
		FBA	18.5	17.8	19.2	15
		FBA – LBA	1.4	0.6	2.2	
		FBA	18.5	17.6	19.5	15
		EIA	18.7	17.4	20.0	8
		FBA – EIA	0.2	-1.4	1.8	
		EIA	18.7	17.0	20.4	8
		LIA	17.3	14.9	19.7	4
		EIA – LIA	-1.4	-4.3	1.5	
	$\delta^{15}\text{N}$	LBA	6.7	6.0	7.4	44
		FBA	6.4	5.2	7.6	15
		FBA – LBA	0.4	-1.8	1.0	
		FBA	6.4	5.2	7.6	15
		EIA	5.4	3.8	7.1	8
		FBA – EIA	-0.9	-3.0	1.1	
		EIA	5.4	2.9	8.0	8
		LIA	5.4	1.8	9.1	4
		EIA – LIA	-0.1	-4.5	4.4	
Bread wheat	$\Delta^{13}\text{C}$	MBA	17.0	15.5	18.5	2
		LBA	16.7	15.8	17.6	6
		LBA – MBA	-0.3	-2.1	1.4	
		LBA	16.7	16.0	17.3	7
		FBA	17.2	16.6	17.8	8
		FBA – LBA	0.5	-0.4	1.4	
		FBA	17.2	16.6	17.8	8
		EIA	18.2	17.6	18.8	8
		FBA – EIA	1.0	0.2	1.9	
	$\delta^{15}\text{N}$	MBA	4.7	-1.2	10.7	2
		LBA	6.3	2.9	9.8	6
		LBA – MBA	1.6	-5.2	8.5	
		LBA	6.3	4.1	8.6	6
		FBA	3.5	1.5	5.4	8
		FBA – LBA	-2.9	-5.9	0.1	
		FBA	3.5	2.0	4.9	8
		EIA	4.8	3.3	6.2	8
		FBA – EIA	1.3	-0.7	3.3	

Note. Variances are assumed equal, so s_p was used to calculate each CI.

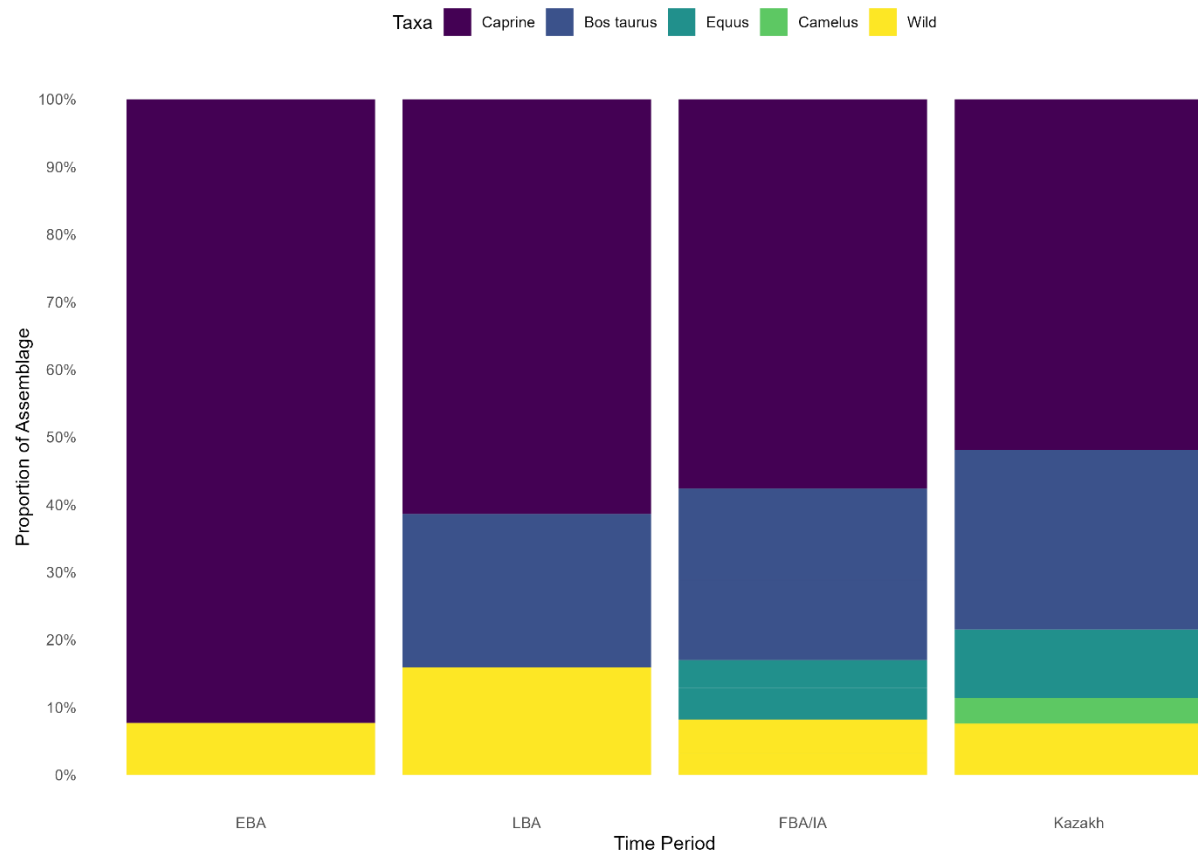
Supplementary Table 15. Percentages (%) and counts (N) of taxa, grouped by habitat type: Grassland, Ruderal, and Wetland, for Tasbas phases Early Bronze Age (EBA), Middle Bronze Age (MBA), Late Bronze Age (LBA), Final Bronze Age (FBA), Early Iron Age (EIA), Late Iron Age (LIA), and Kazakh period (Kaz)

	EBA		MBA		LBA		FBA		EIA		LIA		Kaz	
	%	N	%	N	%	N	%	N	%	N	%	N	%	N
Grassland		0	4%	12	10%	479	7%	143	7%	223	50%	175		
Asteraceae							0%	1			1%	4		
<i>Artemesia</i> sp.					2%	103	3%	59	1%	43				
<i>Asteraceae</i>														
Fabaceae					0%	1								
cf. <i>Astragalus</i>					0%	1								
Poaceae			4%	12	8%	373	4%	79	6%	180	48%	170		
cf. <i>bromus</i>					0%	1								
cf. <i>digitaria</i>			2%	6	0%	8			2%	72	29%	101		
<i>Panicoid</i> -Type					2%	89	1%	28	1%	38	8%	27		
<i>Poaceae</i> spp.			1%	4	0%	23	0%	1	1%	33	2%	6		
<i>Pooid</i> -Type			0%	1	1%	35	1%	15	0%	4	4%	13		
<i>Stipa</i> -Type			0%	1	5%	217	2%	35	1%	33	7%	23		
Solanaceae					0%	2	0%	4			0%	1		
<i>Solanaceae</i>					0%	2	0%	4			0%	1		
							126							
Ruderal	38%	3	63%	172	79%	3683	60%	7	46%	1481	42%	147	55%	16
Alliaceae					0%	3								
<i>Alium</i> sp.					0%	3								
Amaranthaceae														
<i>Amaranthus</i> sp.			3%	7	1%	30	2%	37	0%	7				
<i>Cheno-ams</i>	13%	1	9%	25	3%	134	16%	340	9%	284	1%	2		
<i>Chenopodium</i> spp.	13%	1	46%	126	23%	1069	32%	669	28%	921	33%	117	52%	15
Boraginaceae					0%	2			0%					
<i>Lithospermum</i>														
<i>arvense</i>					0%	2			0%					
Brassicaceae					0%	1					0%	1		
<i>Thlapsi arvense</i>					0%	1			0%	2	0%	1		
Caryophyllaceae			2%	5	0%	2	0%	4	0%	8	1%	2		
<i>Vaccaria/Saponaria</i>					51%	2362	9%	196	4%	144	2%	6		
Fabaceae					0%	1								
<i>Vicia</i> sp.					0%	1			0%	3				
Lamiaceae					0%	5								
<i>Ajuga</i>					0%	5								
Malvaceae					0%	1								
<i>Malva</i> (cf. <i>sylvestris</i>)					0%	1			0%	1				

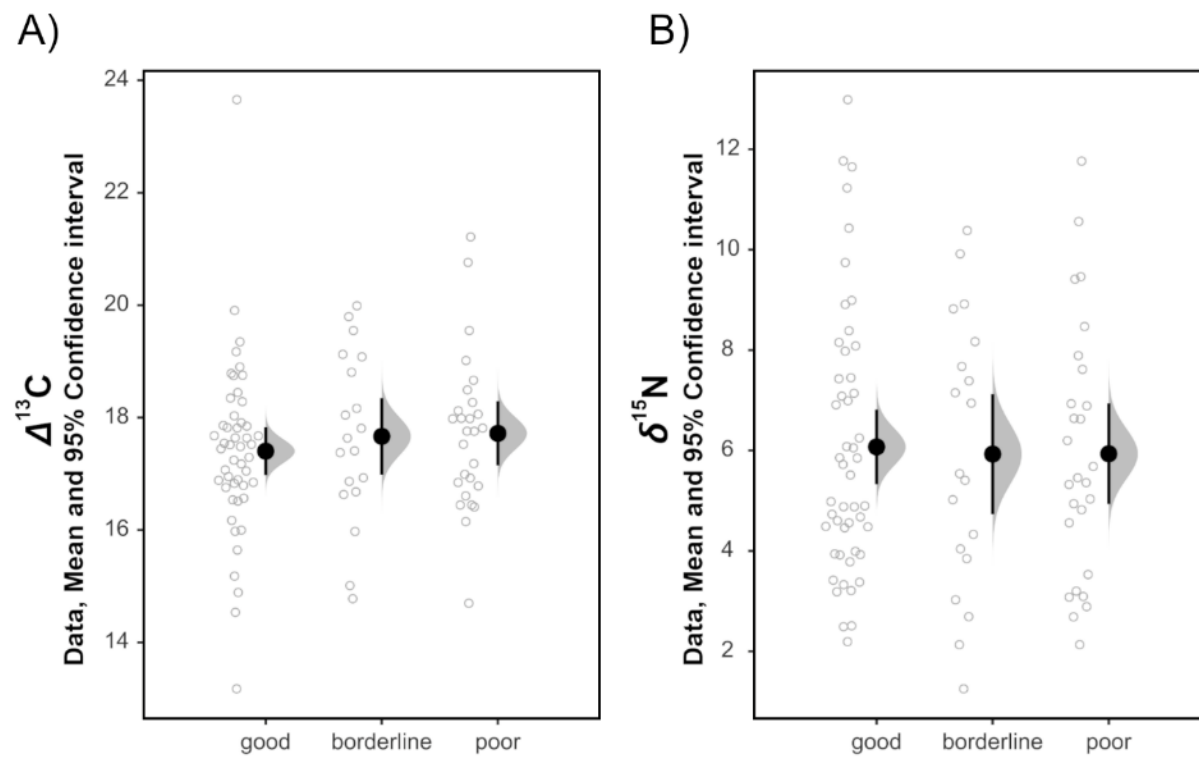
Supplementary Table 15. Continued (Page 2 of 2)

Plantaginaceae <i>Plantago sp.</i>			0% 1								
Poaceae <i>Setaria (cf. viridis)</i> small millet			0% 1 1% 37 1% 37			1% 17 1% 17			5% 18 5% 18		
Rubiaceae <i>Galium sp.</i>	13% 1	3% 9	1% 35	0% 2	2% 75	0% 1	3% 1				
Verbanaceae <i>Veronica</i>				0% 2	0% 7						
Wetland	63% 5	33% 89	10% 471	33% 686	48% 1545	8% 29	45% 13				
Caryophyllaceae <i>Saponaria</i>					0% 1						
Cyperaceae <i>Carex spp.</i> <i>Cyperaceae spp.</i>	13% 1	0% 1 0% 1	0% 6 1% 30	7% 151 0% 3	4% 139 5% 160	1% 2 1% 2	3% 1				
Fabaceae cf. <i>Medicago/</i> <i>Trifolium/</i> <i>Melilotus</i> <i>Galega</i> <i>Trifolium</i> <i>Trigonella-Type</i>		23% 64	4% 179	11% 234	33% 1075 0% 16	0% 1	31% 9				
Juncaceae	50% 4		3% 129	2% 44	0% 1	2% 6					
Polygonaceae <i>Polygonum</i> <i>(persicaria-Type)</i> <i>Polygonum spp.</i> <i>Rumex</i>		8% 21	0% 3 0% 1	4% 76 1% 18	0% 8	1% 2					
Rosaceae <i>Fragaria/Potentilla</i>		8% 21	1% 53	0% 2	2% 81	1% 5					
Solanaceae <i>Hyoscyamus niger</i>		0% 8 0% 10 1% 58 1% 58	0% 8 0% 10 7% 146 7% 146	0% 10 1% 45	0% 10 3% 11 3% 11	10% 3 10% 3					

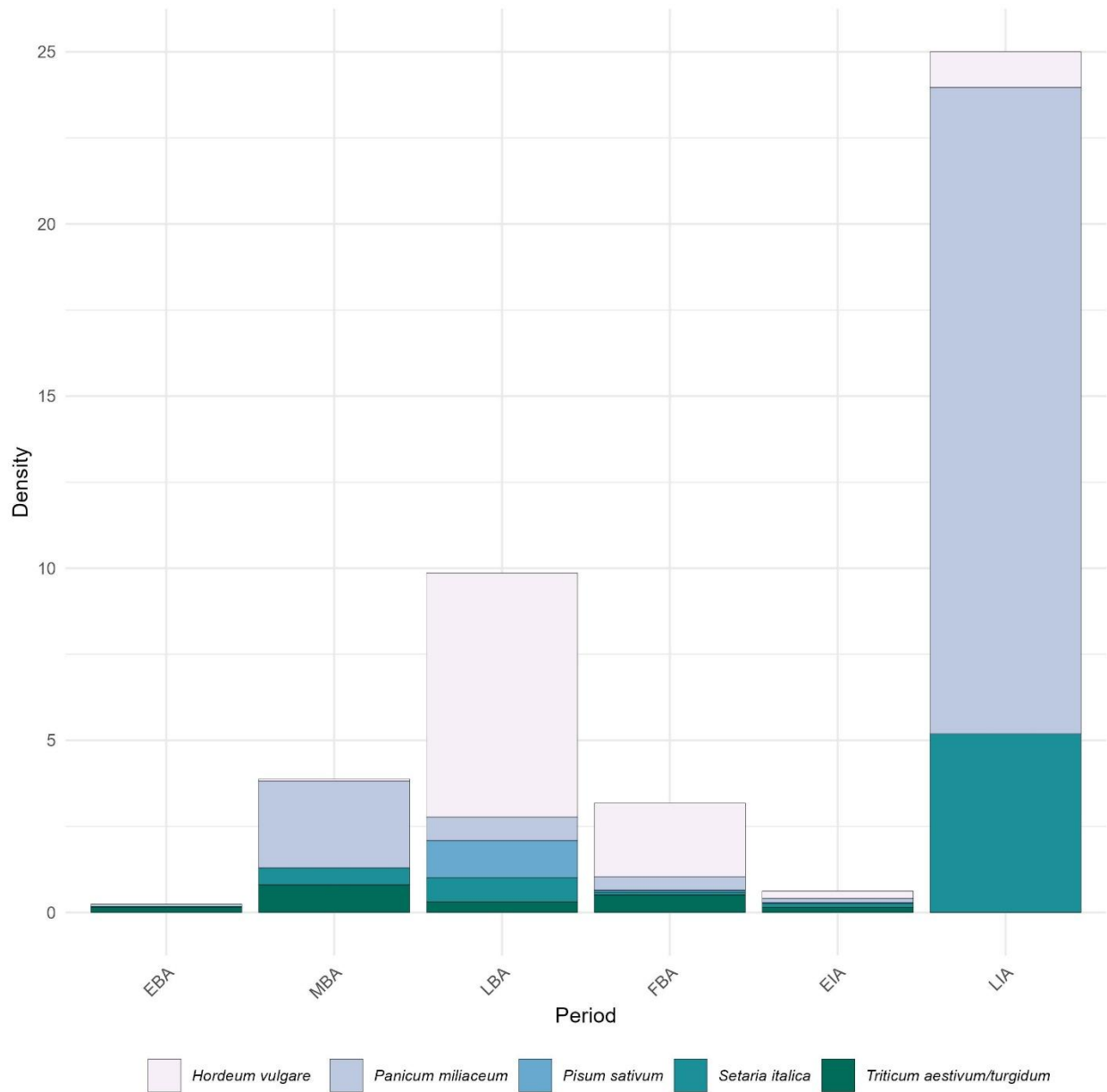
Appendix 5. Chapter 3 Supplementary Figures



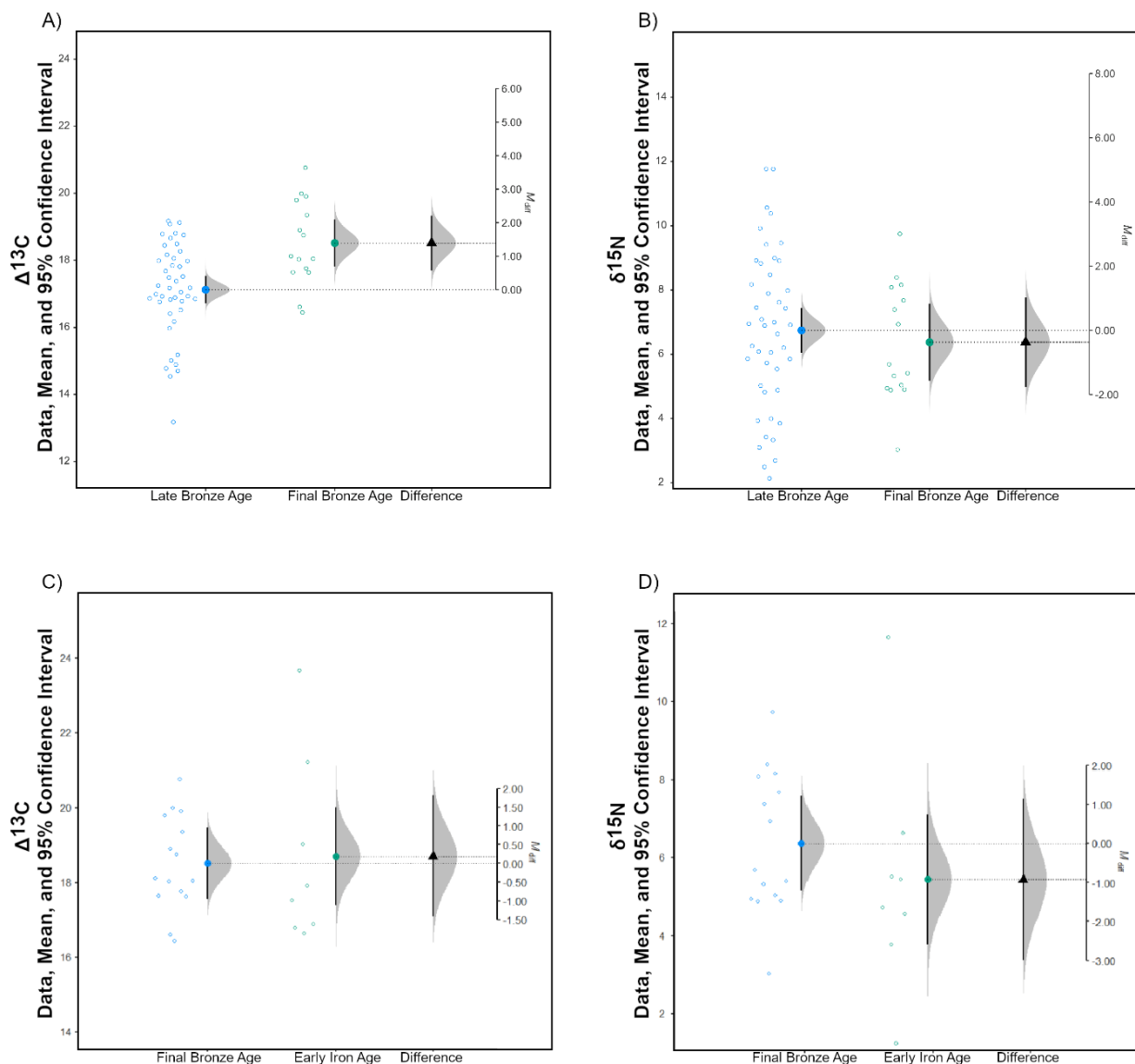
Supplementary Figure 6. Bar chart of NISP (number of identified specimens) as a proportion of total fauna remains from the 2011 Tasbas excavation. Data from Doumani et al. 2015.



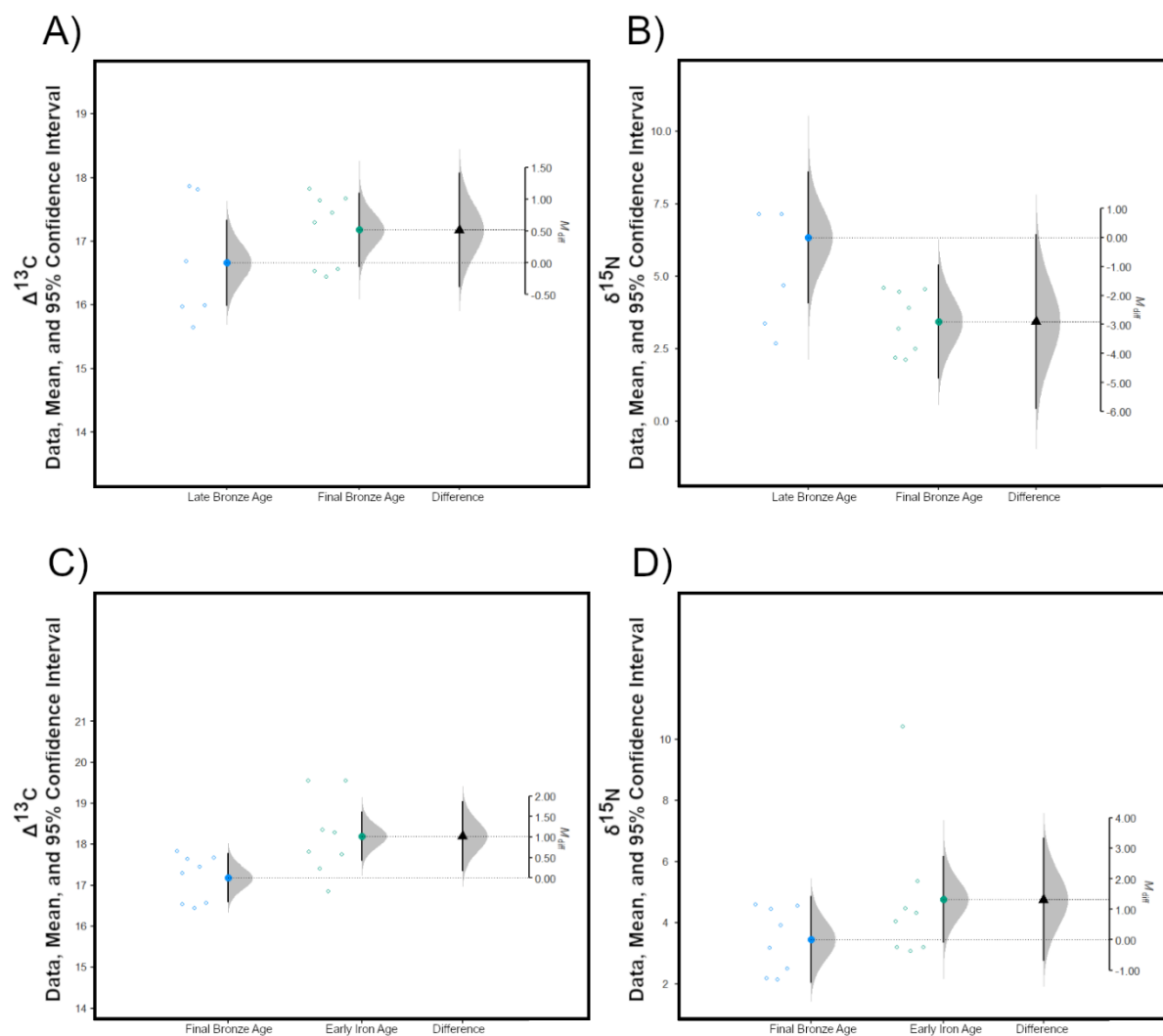
Supplementary Figure 7. Estimation figure of the 95 CIs of A) $\Delta^{13}\text{C}$ values and B) $\delta^{15}\text{N}$ values of the qualitatively assigned charring status of grains from Tasbas.



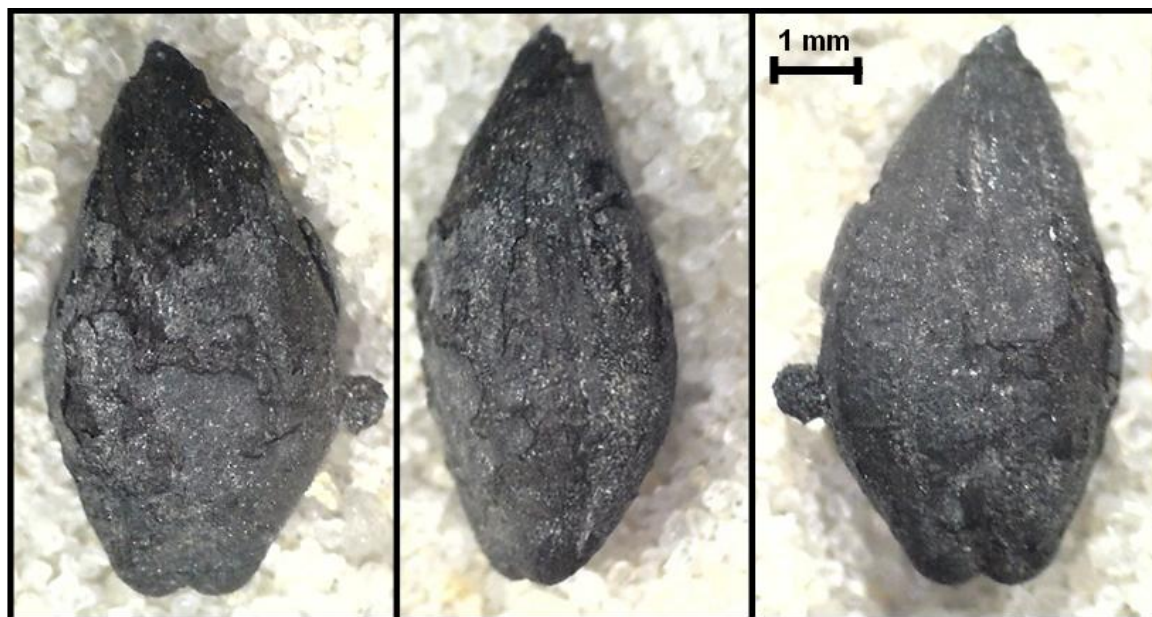
Supplementary Figure 8. Stacked bar charts displaying the densities of identified domestic seed and seed fragments through all time periods at Tasbas: Early Bronze Age (EBA), Middle Bronze Age (MBA), Late Bronze Age (LBA), Final Bronze Age (FBA), Early Iron Age (EIA), and Late Iron Age (LIA). Data available in Table 6.



Supplementary Figure 9. Independent groups contrast comparing the 95 % CIs of barley A) $\Delta^{13}C$ from LBA to FBA, B) $\delta^{15}N$ from LBA to FBA, C) $\Delta^{13}C$ from FBA to EIA, and D) $\delta^{15}N$ from FBA to EIA at Tasbas. The floating axis on the right shows the best estimate for the mean difference (M_{diff}) between the time periods.



Supplementary Figure 10. Independent groups contrast comparing the 95 % CIs of free-threshing wheat A) $\Delta^{13}C$ from LBA to FBA, B) $\delta^{15}N$ from LBA to FBA, C) $\Delta^{13}C$ from FBA to EIA, and D) $\delta^{15}N$ from FBA to EIA at Tasbas. The floating axis on the right shows the best estimate for the mean difference (M_{diff}) between the time periods.



Supplementary Figure 11. Example of hulled barley grain from Tasbas recovered from an Early Iron Age flotation sample 18, OP 4, context 25/29C. Images from left to right: dorsal, lateral, ventral.

Appendix 6. Chapter 4 Supplementary Tables

Supplementary Table 16. Data for analyses of individual barley grains, including: $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, $\Delta^{13}\text{C}$, % C, % N, CN ratio, grain size measurements, and assigned charring status. A blank grain metric indicates incomplete grain due to taphonomic or preservation processes.

Lab ID	Context	Barley type	$\delta^{15}\text{N}$	$\delta^{13}\text{C}$	$\Delta^{13}\text{C}$	%C	%N	CN	Length	Breadth	Thickness	L/B ratio	Charring status
Piyang													
PY3_2_2	2019 PY3②	naked	15.1	-21.8	15.6	69.5	1.9	39.8	4.75	3.05	1.94	1.56	poor
PY3_2_3	2019 PY3②	naked	15.0	-22.3	16.2	60.4	1.9	34.2	4.29	2.74	2.09	1.57	good
PY3_2_4	2019 PY3②	naked	11.2	-21.4	15.2	69.5	2.5	29.9	4.27	2.76	2.01	1.55	poor
PY3_2_5	2019 PY3②	naked	13.8	-22.9	16.7	74.0	2.4	32.9	4.26	2.88	2.07	1.48	borderline
PY3_2_6	2019 PY3②	naked	13.1	-22.3	16.2	70.7	1.9	39.5	5.40	3.55	2.12	1.52	poor
PY3_2_7	2019 PY3②	naked	17.2	-22.4	16.3	59.7	2.9	22.1	5.11	3.60	2.41	1.42	good
PY3_2_8	2019 PY3②	naked	15.6	-21.8	15.6	65.9	3.3	20.2	5.29	3.44	2.72	1.54	poor
PY3_2_9	2019 PY3②	naked	13.5	-21.9	15.7	63.0	2.8	22.3	4.82	3.4	2.06	1.42	poor
PY3_2_10	2019 PY3②	naked	13.3	-22.6	16.5	61.6	3.6	17.2		2.84	1.58		poor
JWT04HT1_1	2019 JWT04 HT1	naked	14.9	-21.4	15.2	70.6	2.5	30.6	4.92	3.29	2.25	1.5	borderline
JWT04HT1_2	2019 JWT04 HT1	naked	12.7	-23.9	17.8	73.0	2.5	31.7	5.20	4.02	2.64	1.29	poor
JWT04HT1_3	2019 JWT04 HT1	naked	15.0	-23.2	17.1	68.8	3.2	23.3	4.88	3.38	2.77	1.44	borderline
JWT04HT1_4	2019 JWT04 HT1	naked	13.3	-21.9	15.8	68.6	4.9	15.0	5.39	2.95	2.52	1.83	borderline
JWT04HT1_5	2019 JWT04 HT1	naked	15.0	-23.9	17.8	73.9	2.2	36.3	5.00	2.99	2.40	1.67	poor
JWT04HT1_6	2019 JWT04 HT1	naked	11.7	-23.9	17.8	73.8	3.3	24.6	4.42	3.07	2.40	1.44	borderline
JWT04HT1_7	2019 JWT04 HT1	naked	14.8	-22.6	16.5	70.9	2.6	29.6	5.56	3.17	2.57	1.75	borderline
JWT04HT1_8	2019 JWT04 HT1	naked	14.6	-22.2	16.1	71.6	2.6	29.8	4.82	3.60	2.47	1.34	poor
JWT04HT1_9	2019 JWT04 HT1	naked	14.1	-22.6	16.5	72.5	3.0	26.5	6.16	3.19	2.23	1.93	poor
JWT04HT1_10	2019 JWT04 HT1	naked	10.9	-19.8	13.6	71.0	3.4	21.2	5.19	3.49	2.25	1.49	poor
JWT04HT1_11	2019 JWT04 HT1	naked	13.8	-22.6	16.5	66.9	4.9	13.6	6.63		2.97		borderline
JWT04HT1_12	2019 JWT04 HT1	naked	10.7	-24.6	18.5	66.5	4.3	15.5		3.62	2.24		poor
JWT04HT1_13	2019 JWT04 HT1	naked	17.3	-22.9	16.8	60.9	5.0	12.1	5.25	3.03	1.81	1.73	poor
JWT04HT1_14	2019 JWT04 HT1	naked	15.7	-22.6	16.5	61.1	4.6	13.4	5.55	4.11	2.39	1.35	borderline
JWT04HT1_15	2019 JWT04 HT1	naked	12.5	-21.5	15.3	63.7	4.6	13.9	5.49	2.83	1.95	1.94	poor
JWT04HT1_16	2019 JWT04 HT1	naked	9.5	-22.1	15.9	67.1	5.0	13.4	5.57	3.12	2.03	1.79	poor
JWT04HT1_17	2019 JWT04 HT1	naked	12.8	-22.1	15.9	67.2	3.0	22.3	4.88	3.13	2.31	1.56	poor
JWT04HT1_18	2019 JWT04 HT1	naked	12.2	-21.7	15.5	71.8	3.4	21.2	4.48	2.85	2.26	1.57	poor
JWT04HT1_19	2019 JWT04 HT1	naked	14.2	-22.1	16.0	69.7	2.7	25.9	4.03	2.52	1.96	1.6	poor
DDHD1_N1	2019 DD HD1	naked	16.7	-21.7	15.5	71.0	2.3	33.4	5.89	3.15	2.44	1.87	borderline
DDHD1_N2	2019 DD HD1	naked	17.3	-22.5	16.4	70.5	2.6	28.9	6.06	3.13	2.34	1.94	good

Supplementary Table 16. Continued (Page 2 of 2)

DDHD1_N3	2019 DD HD1	naked	17.3	-21.5	15.3	63.7	2.9	24.1	5.39	2.95	2.84	1.83	poor
DDHD1_N4	2019 DD HD1	naked	16.6	-21.4	15.3	70.9	2.8	27.5	5.70	3.30	2.29	1.73	borderline
DDHD1_N5	2019 DD HD1	naked	12.0	-21.5	15.3	71.2	2.2	34.8	5.51	2.83	1.89	1.95	poor
DDHD1_N6	2019 DD HD1	naked	18.1	-20.9	14.7	69.0	3.0	24.6	5.27	3.18	2.66	1.66	good
DDHD1_N7	2019 DD HD1	naked	18.3	-22.4	16.3	68.9	2.7	28.0	5.03	3.16	2.46	1.59	poor
DDHD1_N8	2019 DD HD1	naked	16.5	-21.5	15.3	71.8	2.6	29.6	5.21	2.69	2.14	1.94	borderline
DDHD1_N9	2019 DD HD1	naked	17.3	-22.4	16.3	71.5	2.6	29.9	6.12	3.81	2.45	1.61	good
DDHD1_N10	2019 DD HD1	naked	17.7	-21.3	15.1	66.9	3.3	21.9	6.28	3.01	2.59	2.09	poor
DDHD1_N11	2019 DD HD1	naked	15.2	-24.0	17.7	63.1	3.1	20.3	5.85	3.62	3.03	1.62	poor
DDHD1_N12	2019 DD HD1	naked	18.7	-22.1	15.8	64.3	3.9	16.6	5.63	3.47	2.36	1.62	good
DDHD1_N13	2019 DD HD1	naked	18.6	-21.7	15.3	65.3	3.7	17.7	6.39	3.97	2.61	1.61	borderline
DDHD1_N14	2019 DD HD1	naked	19.8	-22.2	14.2	62.8	3.2	19.8	6.05	3.08	2.46	1.96	poor
DDHD1_N15	2019 DD HD1	naked	13.0	-20.6	15.7	67.9	2.9	23.7	5.65	3.84	2.52	1.47	poor
DDHD1_N17	2019 DD HD1	naked	17.3	-22.1	15.4	64.1	4.2	15.1	5.79	3.38	2.78	1.71	poor
DDHD1_N18	2019 DD HD1	naked	16.1	-21.8	15.5	66.7	3.8	17.7		3.15	2.31		good
DDHD1_N19	2019 DD HD1	naked	17.2	-21.9	16.7	65.6	3.4	19.1		3.26	2.54		poor
DDHD1_N20	2019 DD HD1	naked	18.6	-23.1	15.3	67.2	4.1	16.2		2.21			good
DDHD1_H1	2019 DD HD1	hulled	15.9	-21.6	16.1	66.8	3.1	23.4	6.72	2.51	1.73	2.68	poor
DDHD1_H2	2019 DD HD1	hulled	14.5	-21.2	15.0	67.0	2.7	26.8	6.18	2.27	1.76	2.72	borderline
DDHD1_H3	2019 DD HD1	hulled	18.1	-20.9	14.7	68.8	3.6	20.6	7.01	2.66	1.97	2.64	poor
DDHD1_H4	2019 DD HD1	hulled	14.5	-20.8	14.6	32.9	1.2	31.9	6.43	2.42	1.49	2.66	poor
DDHD1_H5	2019 DD HD1	hulled	18.6	-21.6	15.5	68.1	3.4	23.6	5.62	2.99	1.72	1.88	good
DDHD1_H6	2019 DD HD1	hulled	15.4	-21.6	15.4	60.2	2.2	31.6	5.85	2.27	2.21	2.58	borderline
DDHD1_H7	2019 DD HD1	hulled	15.9	-22.2	16.1	67.3	2.1	36.6	6.59	2.41	1.85	2.73	poor
DDHD1_H8	2019 DD HD1	hulled	14.2	-23.3	17.2	18.1	0.6	36.7	5.63	2.99	1.93	1.88	good

Supplementary Table 17. Analysis of confidence intervals and independent group contrasts, displayed in Supplementary Figure 12, between qualitatively assigned charring status and $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of barley grains from Piyang, Jiweng, and Dingdong.

Mean Difference							
Outcome variable	Charring status	M	95% CI		Mdn	s	n
			LL	UL			
$\Delta^{13}\text{C}$	good	15.9	15.3	16.5	16.0	0.7	10
	borderline	16.0	15.5	16.5	15.6	0.9	14
	poor	15.9	15.6	16.3	15.9	1.1	31
$\delta^{15}\text{N}$	good	17.1	15.7	18.5	17.3	1.5	10
	borderline	15.1	13.9	16.3	14.9	1.7	14
	poor	14.5	13.7	15.3	14.5	2.5	31
	poor - good	-2.6	-4.2	-1.0			
Note. Variances are assumed equal, so s_p was used to calculate each CI.							

Supplementary Table 18. Analysis of independent groups contrast, displayed in Supplementary Figure 13, between $\Delta^{13}\text{C}$ values of barley grains between Dingdong and the combined Jiweng and Piyang results, and between Jiweng and Dingdong.

Mean Difference				
Outcome variable	Site Effect	M	95% CI	
			LL	UL
$\Delta^{13}\text{C}$	Piyang	16.0	15.3	16.0
	Jiweng	16.4	16.0	16.8
	Dingdong	15.6	15.3	16.0
	(Dingdong and Piyang)	15.8	15.5	16.2
	(Dingdong and Piyang) – Jiweng	-0.6	-1.1	0.0
	Jiweng – Dingdong	0.9	0.3	1.5
Note. Variances are assumed equal, so s_p was used to calculate each CI.				

Supplementary Table 19. Analysis of independent groups contrast, displayed in Supplementary Figure 14, between $\delta^{15}\text{N}$ values of barley grains from Dingdong and combined Piyang and Jiweng results

Mean Difference				
Outcome variable	Site Effect	M	95% CI	
			LL	UL
$\delta^{15}\text{N}$	(Piyang and Jiweng)	13.8	13.1	14.6
	Dingdong	16.7	15.9	17.4
	(Piyang and Jiweng) – Dingdong	-2.8	-3.9	-1.8
Note. Variances are assumed equal, so s_p was used to calculate each CI.				

Supplementary Table 20. Analysis of independent groups contrast, displayed in Supplementary Figure 15, between $\delta^{15}\text{N}$ and $\Delta^{13}\text{C}$ values of *Hordeum vulgare* var. *vulgare* (hulled) and *Hordeum vulgare* var. *nudum* (naked) grains from Dingdong.

Mean Difference						
Outcome variable	Species Effect	M	95% CI		n	
			LL	UL		
$\delta^{15}\text{N}$	Barley naked	17.0	16.1	17.8	19	
	Barley hulled	15.9	14.5	17.2	8	
	Barley naked – Barley hulled	1.1	-0.5	2.7		
$\Delta^{13}\text{C}$	Barley naked	15.6	15.3	16.0	19	
	Barley hulled	15.6	15.0	16.2	8	
	Barley naked – Barley hulled	0.1	-0.6	0.8		
Note. Variances are assumed equal, so s_p was used to calculate each CI.						

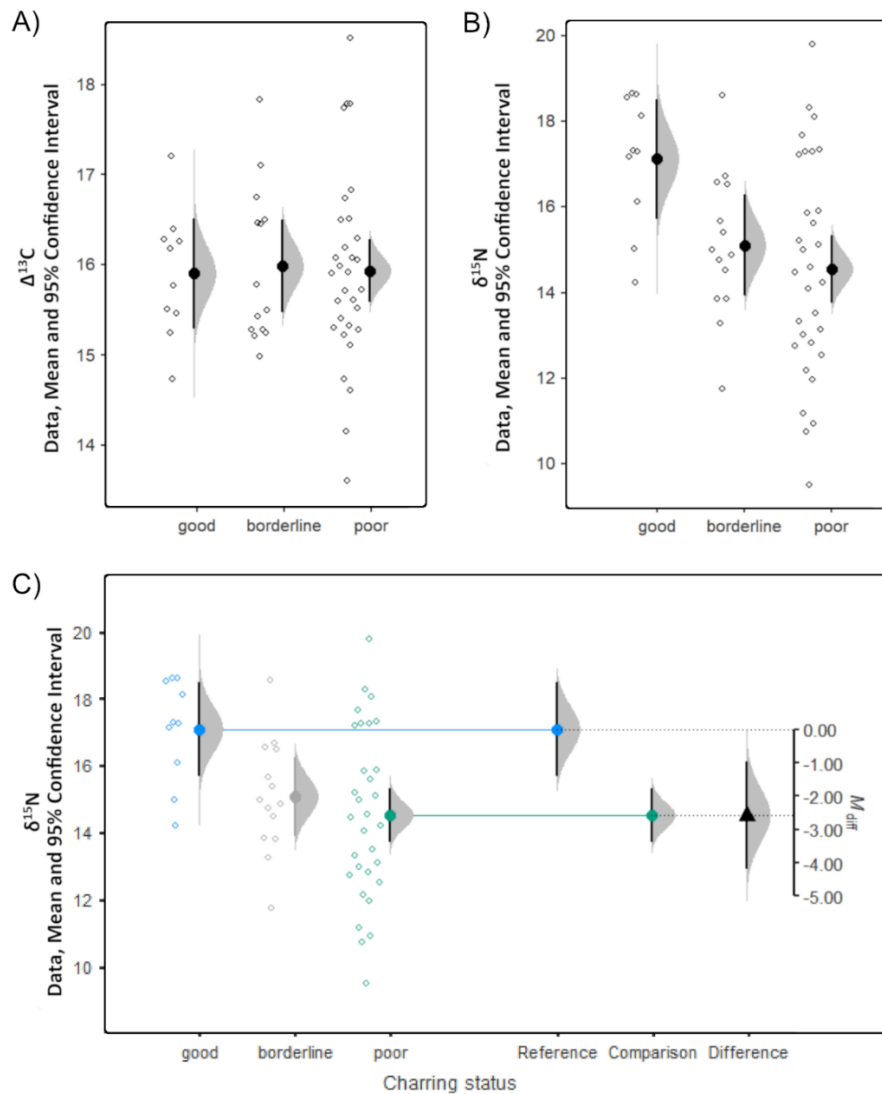
Supplementary Table 21. Analysis of single group correlations, displayed in Figure 20, between $\delta^{15}\text{N}$ and $\Delta^{13}\text{C}$ values and barley grain size measurements from Piyang, Jiweng, and Dingdong. Additional correlations comparing just *Hordeum vulgare* var. *vulgare* (hulled) and *Hordeum vulgare* var. *nudum* (naked) grain grains from Dingdong to their grain size measurements are included.

Linear Correlation					
X variable	Y variable	Pearson's r [95 % CI]	$S_{Y,X}$	N_{pairs}	df
Piyang					
$\delta^{15}\text{N}$	Length	0.39 [-0.47, 0.85]	0.46	8	6
$\delta^{15}\text{N}$	Breadth	0.46 [-0.32, 0.85]	0.34	9	7
$\delta^{15}\text{N}$	Thickness	0.55 [-0.21, 0.88]	0.28	9	7
$\delta^{15}\text{N}$	L/B ratio	-0.25 [-0.80, 0.57]	0.06	8	6
$\Delta^{13}\text{C}$	Length	0.04 [-0.73, 0.68]	0.50	8	6
$\Delta^{13}\text{C}$	Breadth	0.05 [-0.69, 0.64]	0.37	9	7
$\Delta^{13}\text{C}$	Thickness	0.23 [-0.77, 0.52]	0.33	9	7
$\Delta^{13}\text{C}$	L/B ratio	-0.35 [-0.84, 0.49]	0.04	8	6
Jiweng					
$\delta^{15}\text{N}$	Length	0.04 [-0.43, 0.50]	0.63	18	16
$\delta^{15}\text{N}$	Breadth	-0.02 [-0.45, 0.48]	0.42	18	16
$\delta^{15}\text{N}$	Thickness	-0.09 [-0.39, 0.52]	0.30	19	17
$\delta^{15}\text{N}$	L/B ratio	-0.8 [-0.54, 0.42]	0.21	17	15
$\Delta^{13}\text{C}$	Length	-0.02 [-0.48, 0.45]	0.63	18	16
$\Delta^{13}\text{C}$	Breadth	0.23 [-0.37, 0.63]	0.42	18	16
$\Delta^{13}\text{C}$	Thickness	0.26 [-0.23, 0.63]	0.30	19	17
$\Delta^{13}\text{C}$	L/B ratio	0.02 [-0.61, 0.33]	0.21	17	15
Dingdong					
all grains					
$\delta^{15}\text{N}$	Length	-0.03 [-0.38, 0.42]	0.42	24	22
$\delta^{15}\text{N}$	Breadth	0.26 [-0.15, 0.58]	0.46	26	24
$\delta^{15}\text{N}$	Thickness	0.34 [-0.06, 0.63]	0.37	27	25
$\delta^{15}\text{N}$	L/B ratio	-0.23 [-0.58, 0.19]	0.42	24	22
$\Delta^{13}\text{C}$	Length	-0.14 [-0.51, 0.28]	0.51	24	22
$\Delta^{13}\text{C}$	Breadth	0.30 [-0.12, 0.61]	0.46	26	24
$\Delta^{13}\text{C}$	Thickness	0.22 [-0.18, 0.55]	0.38	27	25
$\Delta^{13}\text{C}$	L/B ratio	-0.26 [-0.60, 0.16]	0.42	24	22
Dingdong					
<i>Hordeum vulgare</i> var. <i>nudum</i> (naked)					
$\delta^{15}\text{N}$	Length	0.19 [-0.34, 0.62]	0.40	16	14
$\delta^{15}\text{N}$	Breadth	0.03 [-0.45, 0.48]	0.36	18	16
$\delta^{15}\text{N}$	Thickness	0.24 [-0.25, 0.62]	0.26	19	17
$\delta^{15}\text{N}$	L/B ratio	0.06 [-0.45, 0.54]	0.18	16	14
$\Delta^{13}\text{C}$	Length	-0.01 [-0.49, 0.50]	0.41	16	14

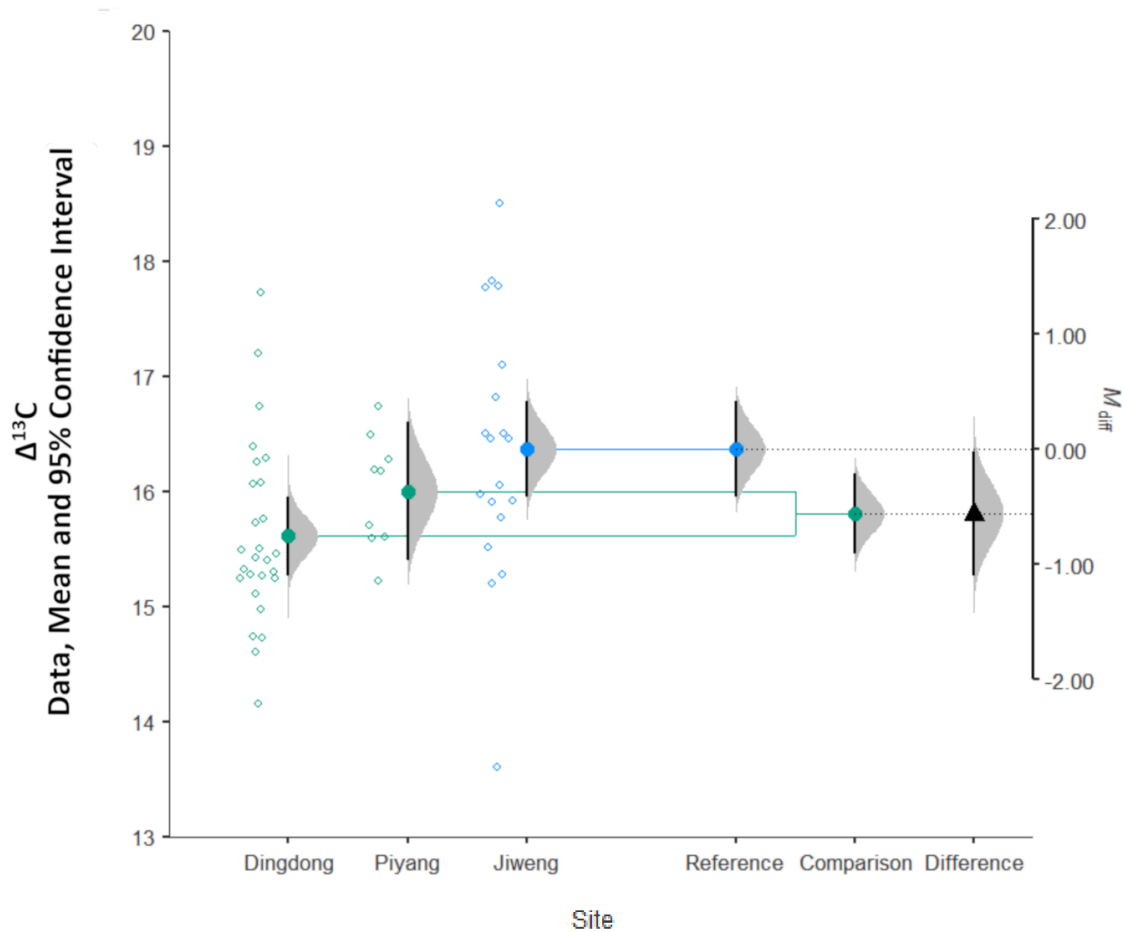
Supplementary Table 21. Continued (Page 2 of 2)

$\Delta^{13}\text{C}$	Breadth	0.34 [-0.16, 0.69]	0.34	18	16
$\Delta^{13}\text{C}$	Thickness	0.31 [-0.18, 0.67]	0.26	19	17
$\Delta^{13}\text{C}$	L/B ratio	-0.40 [-0.74, 0.13]	0.17	16	14
Dingdong					
<i>Hordeum vulgare</i> var. <i>vulgare</i> (hulled)					
$\delta^{15}\text{N}$	Length	0.18 [-0.61, 0.78]	0.55	8	6
$\delta^{15}\text{N}$	Breadth	0.42 [-0.43, 0.86]	0.29	8	6
$\delta^{15}\text{N}$	Thickness	0.10 [-0.66, 0.75]	0.23	8	6
$\delta^{15}\text{N}$	L/B ratio	0.22 [-0.79, 0.59]	0.39	8	6
$\Delta^{13}\text{C}$	Length	-0.40 [-0.85, 0.45]	0.52	8	6
$\Delta^{13}\text{C}$	Breadth	0.47 [-0.38, 0.87]	0.28	8	6
$\Delta^{13}\text{C}$	Thickness	0.26 [-0.56, 0.81]	0.22	8	6
$\Delta^{13}\text{C}$	L/B ratio	-0.51 [-0.89, 0.33]	0.34	8	6

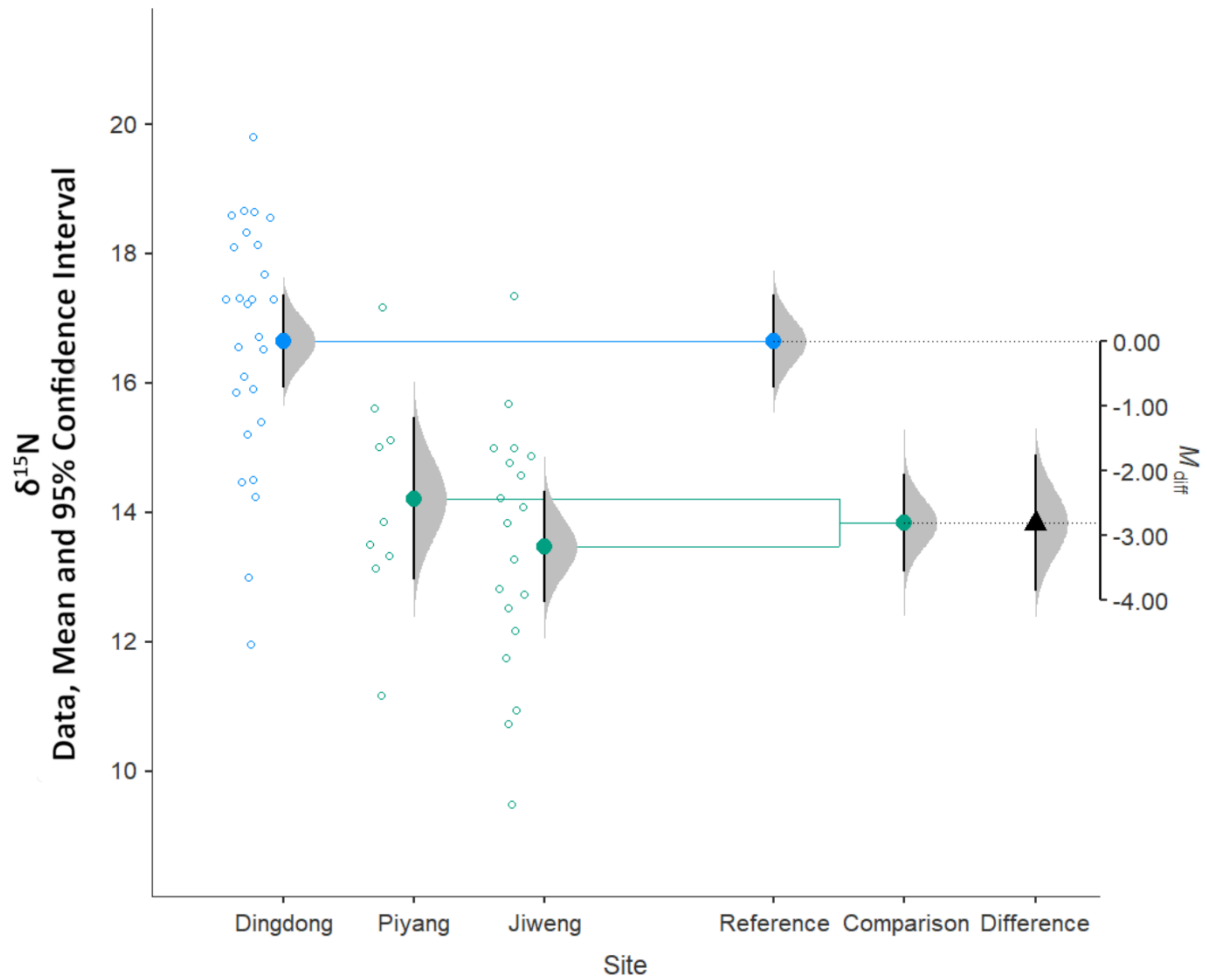
Appendix 7. Chapter 4 Supplementary Figures



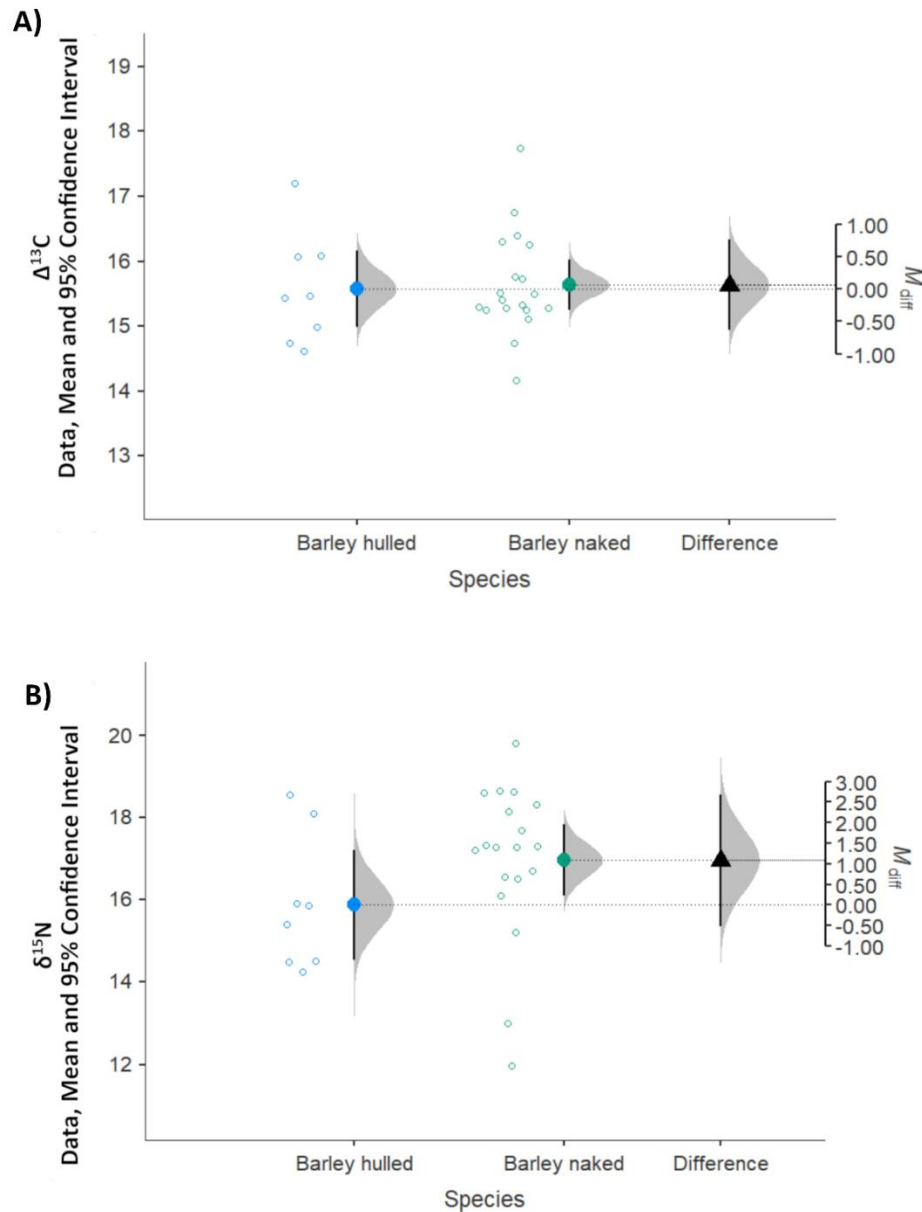
Supplementary Figure 12. Estimation figure of the 95 % CIs of A) $\Delta^{13}\text{C}$ values and B) $\delta^{15}\text{N}$ values of the qualitatively assigned charring status of barley grains from Piyang, Jiweng, and Dingdong. C) Independent group contrast comparing the 95 % CIs of $\delta^{15}\text{N}$ values of good (reference) and poor (comparison) grains from all three sites. The floating axis on the right shows that the best estimate for the mean difference (M_{diff}) between good and poor grains is anywhere between -4.2 and -1.0‰



Supplementary Figure 13. Independent group contrast comparing the 95 % CIs of $\Delta^{13}\text{C}$ values of barley grains from Jiweng (Reference) and Dingdong and Piyang (Comparison). The floating axis on the right shows that the best estimate for the mean difference (M_{diff}) between Dingdong and the grouped data from Jiweng/Piyang is anywhere between -1.1 and -0.0‰.



Supplementary Figure 14. Independent groups contrast comparing the 95 % CIs of $\delta^{15}\text{N}$ values of barley grains from Dingdong (Reference) and Jiweng and Piyang (Comparison). The floating axis on the right shows that the best estimate for the mean difference between (M_{diff}) Dingdong and the grouped data from Jiweng/Piyang is anywhere between -3.9 and -1.8‰



Supplementary Figure 15. Two group contrast comparing the 95 % CIs of A) $\Delta^{13}\text{C}$ and B) $\delta^{15}\text{N}$ values of hulled (*Hordeum vulgare* var. *vulgare*) (reference) and naked (*Hordeum vulgare* var. *nudum*) (comparison) barley grains from Dingdong. The floating axis on the right of A) shows that the best estimate for the difference between (M_{diff}) $\Delta^{13}\text{C}$ of hulled grains and naked grains is anywhere between -0.6 and 0.8 ‰. The floating axis on the right of B) shows that the best estimate for the difference between (M_{diff}) $\delta^{15}\text{N}$ of hulled grains and naked grains is anywhere between -0.5 and 2.7 ‰.

Appendix 8. Chapter 5 Supplementary Tables

Supplementary Table 22. Macrobotanical results from Koken excavations. * denotes uncarbonized seeds.

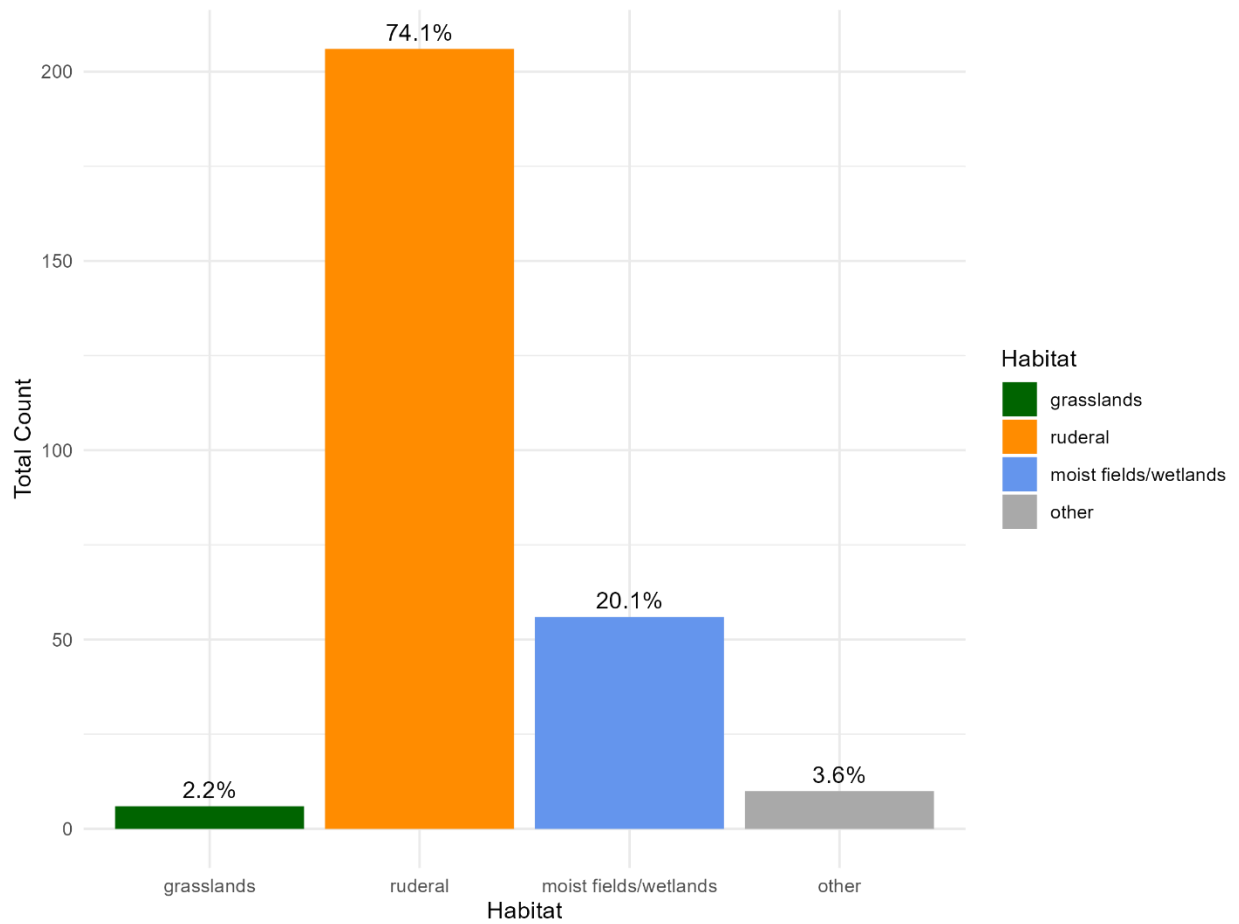
Year 20-	OP	Area	Sample Information				Asteraceae				Amaranthaceae				Brassicaceae	Betulaceae	Caryophyllaceae	Cyperaceae
			Sample	Layer	Time Period	Context	% floated	wood	wood weight (g)	>2mm other	Asteraceae	Amaranthaceae	Cheno/Ams	Cheno/Ams*				
19	8/9	e6	2a	3a	1100-900 (LBA) phase 2	12	30.5	15	NW	7	1?		7					
19	8/9	e6	2b	3a	1100-900 (LBA) phase 2	12	27						28				1	2
19	5/6	d5, d6	10	3a	1100-900 (LBA) phase 2	16	11.5	27	0.19				2		1			
19	2/3	a3	3	3a	1100-900 (LBA) phase 2	18	13						5	1		3		1
19	2/3	b3, b4, a4	1	4	EBA	27	38											
19	2/3	b3, b4, a4	1b	4	EBA	27	33.5	4	NW			17					1	
19	5/6	f6	11	4	EBA	29	2		1.94				1					
19	5/6	F5	15	4	EBA	29	2.4		7.69				1					
19	8/9	F5, F6	4	4	EBA/LBA	31	25.5	NC	NW			1	3		1			
19	8/9	G4, G5, F5, F6	4	4	EBA	32	23						1	12				1
19	8/9	G4, G5, F5, F6	7	4	EBA	32	10.5					2						
19	8/9	G4, G5, F5, F6	7b	4	EBA	32	16		3.26	2		40						
19	2/3	A4	6	4	EBA	24b	22		0.75				43	1				2
20	4	OD	8	1	Ethnographic	14	26		0.87	1	1		>20				1	
20	2	I-J5		2		23	17											
20	2	H4	(a)	3a		27	11	1	NW		1		1					
20	2	H4	(b)	3a		27	0.3											
20	7	E-F98		1		35	19		1.27	6		1	14	>26	8	1		1
20	4	C1		4		39	1.5	2	0.01			2						
20	5	A93-94	(a)	4		40	1.25	3	0.01									
20	5	A93-94	(b)	4		40	1.5											
20	5	C98	(a)	3b	EBA	41	1.25	22	0.1			3						
20	5	C98	(b)	3b	EBA	41	0.8		1.25					3				
20	5	C98	(c)	3b	EBA	41	0.75		1.79									
20	7	H96	18	4		47	3	4	0.04			10						
20	7	I-J97	15	4		45a	1.5			1								
20	7	I-J95	16	4		45b	1.6	3	0.01			2						
20	7	I-J95	17	4		45B	0.3											
20	7	J95	SA17	4		50	4		0.36			1						
22	9	E11	1	1		1	7.5					18	1			1		
22	9	12 D	2	1		1	13.00	7	NW	1	2?		4	4	1	1		
22	12		6	2		3	4.5					1	2			1		
22	8	E8-9	4	4		17B	7	NC		1						1		
22	8	E8-9	8	4		17B	8	31	0.22							2		
22	9	E-F, 11-12	3	3a		5/18	1.2	NC	NW			10						
20	2	I-J5	14	2		23	26					1	2					
12			7			4	3.5											1
12			8			5	4											

Supplementary Table 22. Continued (Page 2 of 2)

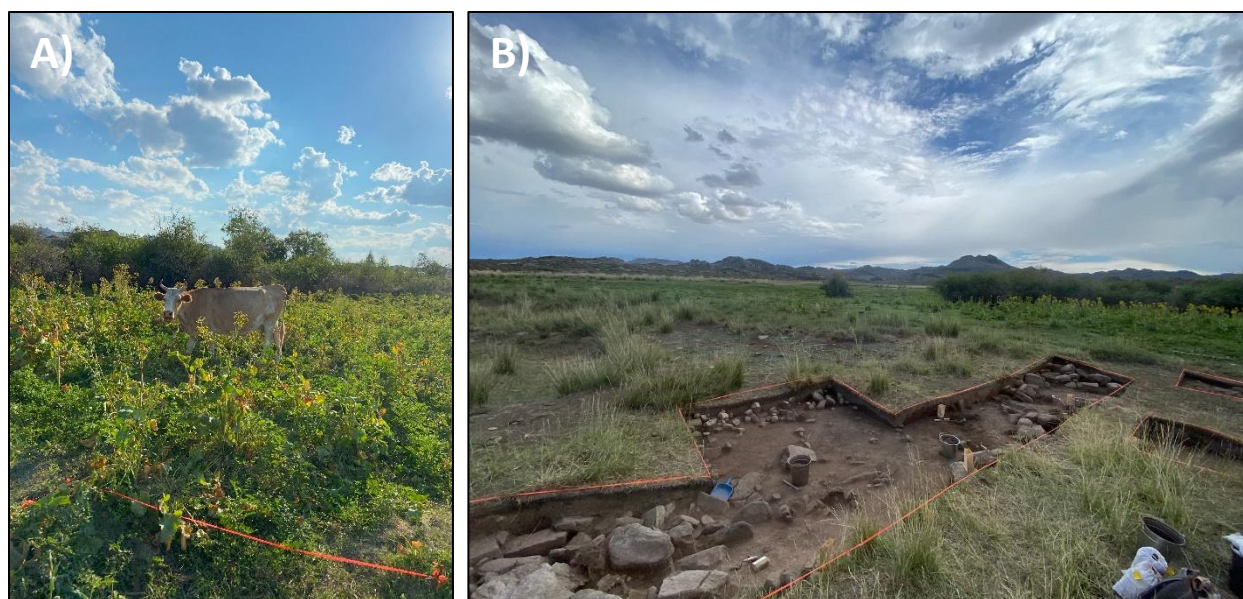
Supplementary Table 23. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from plant remains from Kaerdong and Bangga

Site	Context/Sample	Taxa	Length	Breadth	Height	Condition	count	sample ID	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%TOC	%N	C/N	$\Delta^{13}\text{C}$
Bangga	2017F4Z1?	Hordeum	4.25	2.65	2.55	Good	1	BG.F4Fx82.H1	-22.8	8.9	64.6	4.1	15.6	16.7
Bangga	2017F4Z1?	Hordeum	4.46	3.46	2.72	Good	1	BG.F4Fx82.H2	-21.8	6.7	54.6	3.7	14.8	15.6
Bangga	2017F4Z1?	Hordeum	5.55	3.38	2.73	Poor	1	BG.F4Fx82.H3	-23.7	8.1	57.0	3.1	18.3	17.6
Bangga	2017F4Z1?	Hordeum	4.39	2.73	2.25	Borderline	1	BG.F4Fx82.H4	-24.3	8.4	55.3	4.1	13.6	18.2
Bangga	2017F4Z1?	Hordeum	3.64	2.94	2.19	Borderline	1	BG.F4Fx82.H5	-22.6	8.6	59.9	2.6	23.2	16.4
Bangga	2017III T0101 F1?Fx1	Hordeum	4.31	2.97	2.2	Good	1	BG.F1Fx1.H1	-23.5	5.5	96.4	6.0	16.1	17.4
Bangga	2017III T0101 F1?Fx1	Hordeum	4.21	3.1	2.57	Good	1	BG.F1Fx1.H2	-23.9	4.7	56.0	2.2	24.9	17.9
Bangga	2017III T0101 F1?Fx1	Hordeum	4.63	3.04	2.17	Borderline	1	BG.F1Fx1.H3	-22.5	5.0	55.9	2.7	20.8	16.4
Bangga	2017III T0101 F1?Fx1	Hordeum	3.49	2.32	1.42	Good	1	BG.F1Fx1.H4	-22.0	8.2	56.9	3.5	16.2	15.9
Bangga	2017III T0101 F1?Fx1	Hordeum	4.67	3.32	2.66	Borderline	1	BG.F1Fx1.H5	-21.9	5.7	60.7	2.9	20.6	15.8
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.27	2.44	2	Borderline	1	BG.F1.FX61.H1	-22.0	5.4	53.4	3.1	17.2	15.9
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.6	2.71	2.1	Good	1	BG.F1.FX61.H2	-23.2	6.0	59.5	3.5	17.0	17.1
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.17	3.18	2.38	Good	1	BG.F1.FX61.H3	-26.0	2.4	57.2	4.2	13.6	20.0
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	5.77	2.64	1.77	Borderline	1	BG.F1.FX17.H1	-27.0	3.9	51.5	4.0	12.8	21.0
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.55	2.86	2.09	Good	1	BG.F1.FX17.H2AVG	-22.7	6.3	56.5	2.4	23.2	16.6
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	3.93	2.58	2.06	Borderline	1	BG.F1.FX17.H3	-23.1	6.3	55.6	2.3	23.9	17.0
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.96	3.12	2.56	Poor	1	BG.F1.FX17.H4	-24.1	5.3	56.0	2.8	19.9	18.0
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	5.64	3.54	3.1	Borderline	1	BG.F1.FX17.H5	-23.8	4.4	58.7	2.4	24.9	17.7
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.63	3.26	2.85	Borderline	1	BG.F1.FX32.H1	-24.3	4.5	56.8	3.9	14.5	18.3
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.26	2.24	2.08	Poor	1	BG.F1.FX32.H2	-24.2	0.7	61.1	2.8	21.8	18.1
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	4.91	3.72	2.52	Borderline	1	BG.F1.FX32.H3	-25.9	4.8	53.3	3.0	17.7	19.9
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	3.76	2.86	1.93	Borderline	1	BG.F1.FX32.H4	-25.1	4.2	58.7	2.5	23.9	19.1
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	3.28	2.1	1.28	Good	1	BG.F1.FX32.H5	-25.1	6.6	56.9	3.2	17.8	19.1
Bangga	2017QBIHT0101 F1?IIFx61	Hordeum	3 grains broke in transit, ran together					3 BG.F1.FX61.H456	-26.0	2.4	57.2	4.2	13.6	-21.7
Kaerdong	XZKBLT1?	Hordeum	4.65	2.15	1.76	Poor	1	KD.T1.5.H1	-22.1	17.9	24.9	1.5	16.4	15.9
Kaerdong	XZKBLT1?	Hordeum	4.45	2.17	1.66	Poor	1	KD.T1.5.H2AVG	-24.2	11.5	72.1	3.4	21.3	18.1
Kaerdong	XZKBLT1?	Hordeum	6.69	3.14	1.97	Borderline	1	KD.T1.5.H3	-22.5	14.8	57.5	4.6	12.6	16.4
Kaerdong	XZKBLT1?	Hordeum	5.17	2.81	2.3	Borderline	1	KD.T1.5.H4	-23.1	13.3	63.0	4.4	14.4	17.0
Kaerdong	XZKBLT1?	Hordeum	4.65	3.06	1.83	Good	1	KD.T1.4.H1	-20.6	14.2	65.4	5.5	11.8	14.4
Kaerdong	XZKBLT1?	Hordeum	3.65	2.53	2	Borderline	1	KD.T1.4.H2	-23.1	12.8	58.1	5.8	10.0	17.0
Kaerdong	XZKBLT1?	Hordeum	6.65	3.65	2.59	Poor	1	KD.T1.4.H3AVG	-24.4	15.8	54.7	2.4	22.3	18.3
Kaerdong	XZKBLT1?	Hordeum	5.43	3.2	2.9	Poor	1	KD.T1.4.H4	-21.7	14.0	46.1	2.0	23.2	15.6
Kaerdong	XZKBLT1.6	Hordeum	4.66	2.64	1.74	Poor	1	KD.T1.6.H1	-23.5	13.9	24.6	1.2	21.1	17.4
Kaerdong	XZKBLT1.3	Hordeum	3.62	2.15	1.67	Borderline	1	KD.T1.3.H2	-21.6	10.5	54.0	9.3	5.8	15.4
Bangga	2017QBIHT0101 F1?IIFx61	Chenopodium album					40	BG.F1.FX61.CH1	-28.8	8.5	53.4	5.8	9.2	23.0
Bangga	2017QBIHT0101 F1?IIFx61	Chenopodium album					45	BG.F1.FX32.CH1AVG	-22.2	9.3	39.2	3.5	10.8	16.1
Bangga	2017QBIHT0101 F1?IIFx61	Chenopodium album					40	BG.F1.FX17.CH1	-22.5	9.0	63.0	6.3	10.0	16.4
Kaerdong	XZKBLT1.5	Carex					10	KD.T1.5.C1	-24.1	9.7	64.1	3.8	16.8	18.0
Kaerdong	XZKBLT1.6	Carex					12	KD.T1.6.C1	-23.0	9.7	61.6	6.2	9.9	16.9
Kaerdong	XZKBLT1.4	Carex					10	KD.T1.4.C1	-23.6	11.4	63.8	4.7	13.7	17.5

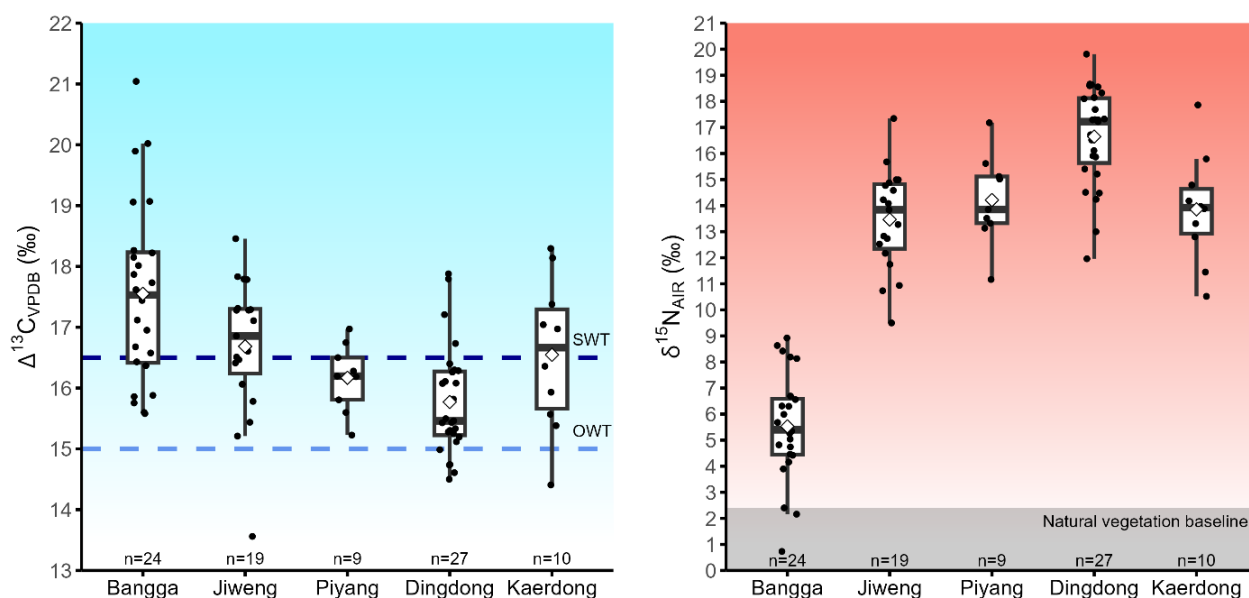
Appendix 9. Chapter 5 Supplementary Figures



Supplementary Figure 16. Summed counts and calculated proportions of taxa categorized by their general habitat type for the site of Koken.



Supplementary Figure 18. Images of the landscape around Koken: A) shrubs and herbs in foreground, with trees along the banks of one of the rivers; B) 2022 excavation unit in foreground, with tree-lined river in the background surrounded by arid-steppe grassland and the Kokentau mountains in the distance.



Supplementary Figure 17. Boxplots displaying $\Delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of barley from all Tibetan sites analyzed in this dissertation, including Dingdong, Jiweng, and Piyang originally presented in Chapter 4 and Bangga and Kaerdong, presented in the Conclusion. Sites are organized in chronological order, from left to right.